1-1-2006

The nature of phonological representation in reading :: evidence from eye movements and event-related potentials/

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THE NATURE OF PHONOLOGICAL REPRESENTATION IN READING:

EVIDENCE FROM EYE MOVEMENTS AND EVENT-RELATED POTENTIALS

A Dissertation Presented

by

JANE ASHBY

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2006

Psychology

UMI Number: 3215898

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DEDICATION

This dissertation is dedicated to my students. Isabel, Natasha,Vernon, Lornanette, and Eli experienced the heart-breaking implications of limited literacy. Will, Emily, Sarah, and Ben showed me the power of effective intervention and the joys of becoming an independent reader.

ACKNOWLEDGMENTS

I would like to thank the many people who made this dissertation possible. Michael and Christine Ashby, Anne Chapman, Sarah Hawrylak, Tami Katzir, Keith Rayner, John Strucker, and Dorothy Whitehead provided support and encouragement. Jeanne Chall, Antje Meyer, Alexander Pollatsek, and Keith Rayner inspired me with their insights into reading and language. Anne Cook, Karen Bradford, and Nancy James comforted me and made me laugh. Above all, I thank my husband Chuck Clifton, who brings me happiness every day. A Kirschstein National Research Service Award from the National Institutes of Health (HD045056) provided financial support for this project. Experiments 1 and 2 were conducted in collaboration with Rebecca Treiman and Brett Kessler at Washington University at St. Louis.

ABSTRACT

THE NATURE OF PHONOLOGICAL REPRESENTATION IN READING:

EVIDENCE FROM EYE MOVEMENTS AND EVENT-RELATED POTENTIALS

MAY 2006

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The present research investigates the relationship between spoken language and reading processes by using several experimental techniques to examine the nature of the phonological representations used during silent reading. Experiments 1 through 4 measured eye movements during sentence reading and lexical decision using a parafoveal preview paradigm. In Experiment 5, brain electrical potentials were recorded in a four-field masked priming paradigm during passive reading of single words. Experiments 1 and 2 asked whether the phonological representations used by skilled readers in lexical access are minimal and contain only consonant information, or whether they include phonological vowel information as well. Experiments 3, 4, and 5 examined whether the phonological representations used in lexical access contain prosodic information about syllables as well as phoneme information. In combination, these experiments demonstrated that skilled readers are sensitive to vowel and prosody information

presented in parafoveal previews and masked foveal primes. This suggests that readers routinely activate elaborate, speech-like phonological representations early in word recognition during silent reading. The phonological hub theory of silent reading is proposed to account for this finding and situate orthographic and phonological processes in the context of natural silent reading.

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CHAPTER 1

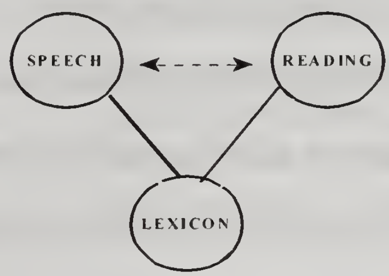
WHAT IS THE RELATIONSHIP OF WRITTEN AND SPOKEN LANGUAGE PROCESSES?

Introduction

Humans process language in several different forms. We express thoughts in writing and by speaking them aloud. We receive information by reading and by listening. Experientially, these activities are quite distinct, and we categorize them accordingly. Speaking and listening group together as *spoken language*, whereas writing and reading are labeled as *written language*. The transparency of these terms is due, in part, to their alignment with our conscious experience of two types of language processes. Speaking is often effortless, whereas writing is laborious. Messages encoded in text are temporally durable, whereas spoken messages are fleeting. Spoken language is thought of as primarily aural and written language as primarily visual. Such differences contribute to the common perception that spoken and written language function as independent communication streams.

Despite these differences, adults and children recognize that both spoken and written language communicate ideas. As we are able to communicate messages in writing and in speech, the message itself appears to occupy a cognitive space that is common to written and spoken language processes, and can be accessed through either. Thus, we intuitively situate the "what" of language in an area of overlap between spoken and written language, whereas the "how" of language (i.e., the act of processing) seems specific to either the spoken or written form. The model that follows from this view conceptualizes spoken and written language as fundamentally separate pathways that converge on a common lexicon. The forthcoming text refers to this intuitive model as *the distinct pathways view*, as illustrated below in Figure 1.

Figure 1. Distinct Pathways View



The distinct language pathways view conceptualizes the common perception of spoken and written language as largely separate processes and, thus, it implicitly licenses computational models of word recognition that depict two independent routes to lexical access. Such dual-route models typically comprise a faster visual (orthographic) route and a slower, rule-based pathway in which letters are converted to sounds (Coltheart, Curtis, Atkins, & Haller, 1995; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). These models conceive of word recognition as the outcome of a race between the two pathways, with the rule-based path winning in the case of unfamiliar letter strings and the visual path winning the rest of the time. Critically, the proposition of a dominant visual route in reading entails the assumption that word recognition processes routinely operate independently of spoken language processes, at least until a word is recognized. In contrast, recent connectionist models of word recognition assume the interactivity of orthographic and phonological processors en route to lexical access (Harm & Seidenberg, 2004).

The distinct pathways view also has influenced how educators think about reading instruction. As in psychology, the claim of distinct processing pathways for spoken and written language licenses the idea that visual processing is central to reading development. Although spoken language is recognized as an important pre-requisite for early literacy, it is considered to be a weak contributor to reading development relative to other factors (e.g., motivation, maturity, number of books in the home). Likewise, improvements in reading fluency tend to be attributed to increased use of the speedy visual route in word recognition, whereas the role of phonological processing in developing fluency is often discounted (Doctor & Coltheart, 1980; Backman, Bruck, Herbert, & Seidenberg, 1984; Condry, McMahon-Rideout, & Levy, 1979). The extreme version of this belief claims that good readers rely purely on the visual route to identify familiar words in reading. Many educators believe that emphasizing print-to-sound relationships in early reading instruction is unnecessary and even damaging for the beginning reader (cf. Smith, 1999). Thus, building a 'direct', visual connection from print to meaning is often the primary goal of early reading instruction. In contrast, Ehri (2005) recognizes the interactivity between phonological and orthographic processing as an engine of reading development that assists with vocabulary acquisition as well as improvement in spelling.

According to the distinct pathways model, spoken and written language processes function independently up to the point of access to the semantic system. As this intuitive view aligns with our conscious experience of reading, its validity seems apparent. Despite the general appeal of this view, it has been challenged by cognitive psychologists who have considered whether silent reading might utilize aspects of spoken language processes.

Nearly a century ago, Huey (1908/1968) claimed that reading draws on the processes that also subserve spoken language. He observed that reading involves hearing the text inside one's head and labeled this phenomenon *inner speech*.

> ...I can never escape the inner pronunciation that forms a part of all my reading...The simple fact is that the inner saying or hearing of what is read seems to be the core of ordinary reading, the 'thing in itself', so far as there is such a part of such a complex process. The child comes to his first reader with his habits of spoken language fairly well formed...[h]is meanings inhere in this spoken language and belong but secondarily to the printed symbols...(p.122-123)

Here, Huey identifies the experience of inner speech as central to reading, and this implies that the spoken language system is the principal processor during reading. Essentially, Huey describes a processing hierarchy, in which spoken language serves as the primary system to which reading processes are appended. According to this view, spoken and written language share multiple processing pathways that allow readers to access spoken word forms (or *lexemes*) as well as word meanings (or *lemmas*). This view is somewhat counterintuitive, as it conceives of reading processes largely as an appendage to the spoken language system. Consistent with Huey's hypothesis, Kosslyn and Matt (1977) demonstrated an influence of speech on silent reading. Participants' silent reading rate was measured as they read passages that were supposedly written by fast talkers and slower talkers. When an author spoke at a slower rate, readers read their passages more slowly than when the same passage was attributed to a fast talking author. Both Huey's view and the Kosslyn and Matt (1977) data are consistent with the distinct pathways view, if one assumes that reading interfaces with the spoken language system after a word is identified in the lexicon.

The term "spoken language system" refers to the cognitive processes involved in the perception and/or production of speech. Huey noted the difficulty of distinguishing between perception and production processes in inner speech during reading. This is due in part to the intuition that a reader reconstructs the speech sounds from a text before he or she "hears" it as inner speech. For example, when reading a letter from your mother, you must first recreate her speech from the text and then you can easily 'hear' her voice as you read (Rayner & Pollatsek, 1989; Brown, 1970). For the purpose of this thesis, the spoken language system is conceptualized as unified – i.e., sharing one phonological store. This is not necessarily the case, as the relationship between production and perception systems is still under investigation. Since that relationship is not a topic of this thesis, I assume a unified system largely out of convenience and focus on the relationship between spoken and written language processes.

As the excerpt from Huey suggests, proficient readers often describe an awareness of the sound of text as they read silently. This inner-speech is presumed to be our conscious awareness of phonological representations. Phonological representations are the abstract codes that describe the sound form of a printed word. In terms of speech production models (Dell, 1986; Dell, Burger, & Svec, 1997; Levelt, Roelefs, & Meyer, 1999), speakers activate phonological representations after accessing a word's lemma (i.e., its meaning and syntactic role). The phonological representation serves as a plan for recruiting the full set of articulatory movements needed to speak a word. Phonological representations are usually considered to exist independent of the motor programs involved in actual speech, although some gestural phonologists claim that phonological representations include motor programs (Browman & Goldstein, 1986). In any case, a phonological representation, or an image of how a word sounds, can be held in one's mind without the word actually being spoken. Intuitively, then, phonological representation may be involved in our thoughts as well as our speech.

Reading researchers have established that skilled reading involves the phonological representation of text, and I discuss this evidence in Chapter 2. The process of accessing and generating phonological representations during reading is often referred to as *phonological coding,* which is an automatic process of converting visual symbols (letters, in the case of English) into spoken word forms. There is ample evidence for the use of phonological coding by developing and skilled readers, but the nature of that coding process is not yet understood. Consequently, we are only beginning to understand the nature of phonological representations in silent reading.

A connection between spoken and written language processes was established decades ago, through the ground-breaking research at Haskins Laboratories (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Liberman & Mattingly, 1989). This research culminated in an *unconventional motor theory of speech*, which states that the basic constituents of speech are articulatory gestures rather than sounds. I.Liberman, Shankweiler, and Liberman (1989) applied this theory to reading and claimed that successful readers access phonology. Experiments conducted at Haskins Laboratories in the 1990's were fundamental in establishing the necessary connection between understanding the phonological basis of written words and reading development. Although this body of research indicated the importance of phonological representations in learning to read, it did not fully specify the nature of those representations in reading.

Statement of Purpose

To date, few researchers have applied the phonological principles of spoken language to examine the nature of phonological representations in reading (relevant studies are discussed in Chapter 3). Consequently, the extent of the similarity between the phonological representations used in reading and in spoken language is largely undetermined. Therefore, the present experiments examined the nature of the phonological representations routinely used in reading and how these representations compare to phonological representations used to process spoken language.

The present research investigates when readers begin processing phonological representations that are similar to those used in spoken language. Since words need not be spoken or heard during silent reading, it is possible that skilled readers use specialized phonological representations for word recognition that contain less information than the representations used in spoken language processing. In that case, elaborate spoken language representations would not be activated until the time of word identification, consistent with the distinct pathways model. Alternatively, skilled readers could begin activating complex phonological representations early in word recognition in the process of feeding text information to the spoken language system before lexical access, and this would be inconsistent with the distinct pathways model. These two possibilities motivate the following examination of the extent to which proficient reading utilizes spoken language representations and for what purposes. The present experiments help clarify the role of phonology in proficient reading by indicating: (a) the specificity of the pre-lexical representation of phonological segment information; (b) the nature of the suprasegmental information contained in the phonological representations in reading; and (c) the probable function of these phonological representations in skilled reading.

Taking a broader perspective, the data collected here may be relevant to understanding how highly automatized, learned skills such as reading interface with core mental processes such as spoken language. Learned skills might develop as cognitive networks that eventually become largely independent of core processes, consistent with the distinct pathways view (McCandliss, Cohen, & Dehaene, 2003). Alternatively, learned skills might "piggy-back" on core processes and take advantage of established networks whenever possible.

CHAPTER 2

PREVIOUS RESEARCH ON

PHONOLOGICAL REPRESENTATION AND READING

This thesis poses several questions about the nature of phonological representation during reading (see Chapter 1). Such questions rest on the assumption of adequate experimental evidence for the use of phonological representations in skilled reading. The following section discusses some of the evidence for phonological coding during skilled reading.

Researchers have studied phonological coding during word recognition in reading by measuring reader responses to homophones, or words in which more than one orthographic form maps onto a single phonological entry (e.g., rein/rain). Homophonic pairs have visually different letter patterns and different meanings, but the words sound identical. The general idea behind homophone experiments is that if response time differences appear for words that have a homophone (rain) as compared to matched words that do not have a homophone (chair), then readers must be processing the spoken word form. In other words, homophone effects arise when word recognition times differ for homophone and nonhomophone targets. The nature of the effects is related to the experimental paradigm, as homophones facilitate processing in naming tasks but seem to interfere in lexical decision. The following review of the literature focuses on lexical decision and semantic categorization paradigms that examined homophone effects during isolated word recognition. More importantly, eye movement experiments measuring fixation times on words in sentence contexts have also found homophone effects.

Homophone effects indicate that readers access the lexeme (e.g. the phonological form of a word) during word recognition. As such, homophone effects are evidence for the use of addressed phonological representations in lexical access. Pseudohomophone experiments, by comparison, use novel orthographic patterns that can be assembled to form a recognizable lexeme (e.g., *brane*). Both homophone and pseudohomophone effects appear consistently in the literature, though more experiments have been conducted with homophones. As many homophone experiments also included a pseudohomophone condition, the following sections are organized mainly by experimental paradigm.

Categorization and Semantic-relatedness Experiments

Van Orden (1987) conducted a series of experiments using a categorization paradigm to investigate the role of phonology in silent word recognition. Participants saw a category name (*flower*) followed by a masked target. They judged whether the target (*rose*) was an exemplar of that category, responded "yes" or "no", and then named the target word. In the critical trials, the target was a homophone of a category member (*rows*), rather than the member itself. In three experiments, participants were more likely to wrongly accept homophones (*rows*) as exemplars of the category (*flower*) than spelling controls (*robs*). In Experiment 1, when the targets appeared for 500 ms, false positives to similarly spelled homophone foils (*meet*, rather than *meat*) were more common (mean= 29%), than to less similarly spelled foils (*rows*, rather than *rose*) (mean=8%). In Experiment 2, Van Orden adjusted the target exposure duration to an individual threshold at which participants could identify most of the exemplars due to semantic priming from the category name, but could not identify the foils. At this shorter exposure duration (less than 150 ms), the mean percentage of false positive responses was 40% and 46% for the similarly spelled and less similarly spelled foils, respectively. Thus, these experiments observed effects of orthographic similarity on the percentage of false positives only when homophone targets were presented at the long duration (500 ms), whereas the shared phonology of the homophone foils and category members increased the percentage of false positives at both long and short target durations. Based on this data, Van Orden proposed his verification account of word recognition to explain the false categorization effect. The verification account claims that phonology initially activates a cohort of lexical entries, and then somewhat later an orthographic spell-check process helps select a specific entry.

Van Orden's verification theory accounts for several data patterns that have previously been claimed to disprove the role of phonology in word recognition. Doctor and Coltheart (1980) observed one such pattern in their frequently cited paper. They conducted a cross-sectional study to examine how children's sensitivity to homophone errors develops over time. Their study found that older children were less likely to accept sentences containing homophone errors than were younger children. Whereas Doctor and Coltheart attributed this result to decreased reliance on phonological coding as reading development progresses (and increased reliance on a visual route), verification theory proposes that the lower acceptance of sentences with homophone errors stems from older children's improved knowledge of word spellings. According to Van Orden (1987), this improved knowledge of spelling permits a more effective spell check process that results in fewer homophone errors. More recently, Drieghe and Brysbaert (2002) conducted a series of lexical decision experiments that support the verification account of early phonological involvement in a word identification task that does not involve overt production. I discuss this study in more detail later in this chapter.

Despite the clear evidence for the verification account, readers should note that the false categorization effect has not always appeared consistently. Some research has shown that homophone categorization effects were specific to the particular homophone foils chosen, or the scope of the categories (e.g., Jared & Seidenberg, 1991). In other studies, increased false positives to homophones as compared to spelling controls did not appear in all measures. For example, when Zeigler, Benraiss, and Besson (1999) recorded event-related potentials, their behavioral data indicated a false categorization effect (19% false positives to the homophone foils), but no significant waveform differences appeared in the N400 to correctly identified category violations on homophone and regular trials. However, it is unclear how to interpret this finding, as their data analysis excluded the false positive trials. Although homophone effects on categorization might not always be apparent, the fact that the effect appears at all with skilled readers suggests that phonological processing plays more than an occasional role in word recognition.

Lesch and Pollatsek (1998) presented pairs of words, with each word appearing on one side of the screen. Participants first fixated the word on the left side, during which time the parafoveal information available from the second word was manipulated. As the eyes moved to the word on the right, the preview changed to the target word. In the main conditions of interest, the second word that the participant fixated was a false homophone or a visually similar control. A false homophone can be pronounced as a homophone of a word, given English spelling conventions. For example, *bead* could be pronounced like *bed* /bɛd/, as though it rhymed with *head*. (Phonetic transcriptions follow the conventions of the International Phonetic Association, 2005). On one trial, *pillow* appeared as the first word, and readers moved their eyes to fixate either *bead* (the false homophone) or *bend* (the control). Participants were slower to reject the false homophone (*bead*) as semantically related to the first word (*pillow*) than to reject the visually similar control (*bend*). The longer reaction time was attributed to participants' generating an alternative pronunciation of *bead* (/bɛd/) that competed as a possible semantic associate of *pillow*. This result suggests that several possible phonological vowels were computed parafoveally based on the preview of the false homophone. Because the false homophone previews affected semantic decisions, it appears that these preliminary phonological codes, which were later rejected, initiated semantic activation.

In summary, categorization and semantic-relatedness experiments indicate that readers are less accurate and/or slower to reject homophones than orthographic controls. For this to occur, readers must be generating the possible phonological forms of printed words. As the homophone lexeme (i.e., spoken word form) connects with multiple semantic representations, it appears that semantic competition complicates the decision process and hinders performance. Overall, these experiments indicate that semantic representations can be activated by preliminary phonological codes, even when those codes are rejected at a later stage, as in the case of the false homophones.

Lexical Decision Experiments

The homophone effect in lexical decision entails longer response times for accepting homophone targets as words, as compared to non-homophonous words. Data from experiments in the 1970's yielded inconsistent homophone effects (Rubenstein, Lewis & Rubenstein, 1971; Coltheart, Davelaar, Jonasson & Besner, 1977). Davelaar, Coltheart, Besner, and Jonasson (1978) claimed that homophone effects appear inconsistently in lexical decision because the phonological route is optional in word recognition. They tested this idea by manipulating the types of nonword foils, using one set of pseudohomophones (*brane*) and one set of non-homophonous nonwords (stape). Davelaar et al. (1978) predicted that with pseudohomophone foils participants would shift away from using phonological codes (to avoid interference from lexical items activated by the pseudohomophones) and make lexical decisions based on orthographic information alone. Conversely, with nonword foils participants were expected to use phonological codes in their decision and, thus, homophone effects would appear. Davelaar et al.'s data bore out these predictions, but they had a flawed experimental design; the word targets in the experiment with the pseudohomophone foils were different from the words presented with the nonword foils. Using foils that orthographically resembled English real words and proper counterbalancing, Pexman, Lupker, and Jared (2001) failed to replicate the Davelaar et al. finding of strategic suppression of phonological processing. Rather, Pexman et al. (2001) found that homophone effects were as large or larger with pseudohomophone foils than nonword foils.

Pexman et al. (2001) claimed that the homophone effect in lexical decision arises from a different source than semantic competition from multiple word meanings. Pexman et al. (2001) noted several studies in which polysemy effects (e.g., *bank*) speeded acceptance responses in lexical decision. Based on these findings, Pexman et al. proposed that homophone effects in lexical decision arise from feedback from competing orthographic representations that interfere with acceptance responses. This process is known as feedback activation.

Feedback activation was first proposed by Stone, Vanhoy, and Van Orden (1997), who observed that lexical decision times were slower when a word's phonological body (hereafter referred to as the *rime*) is spelled several different ways. For example, the rime in *blew* can also be spelled *ue,* which yields the homophone *blue*. Seeing *blew* activates its phonological form, which feeds back to also activate the competing orthographic form *blue*. In contrast, seeing *probe* activates its phonological form, which feeds back activation to the same orthographic form (*probe*). Whereas Peereman, Content, and Bonin (1998) failed to replicate Stone et al. (1997) when consistent and inconsistent words were matched for familiarity, Pexman, Lupker, and Reggin (2002) found reliable orthographic and phonological feedback effects. The Pexman et al. (2002) lexical decision experiment demonstrated inhibitory effects for homographs (*wind*), but found no regularity or homophone effects. Conversely, their phonological lexical decision experiment demonstrated regularity and homophone effects. These data provide further evidence for the interactive processing of orthographic and phonological information, indicating that regularity and homograph effects only appear in tasks that require "fully resolved" phonological codes, but homophone effects appear consistently.

Recently, Drieghe and Brysbaert (2002) conducted a series of lexical decision experiments in Dutch to examine the time course of phonological priming and orthographic feedback. Each target was visually primed by a semantic associate, a homophone of the associate, a pseudohomophone, or a dissimilar control. Participants identified words among orthographically legal nonword foils. At the shorter prime duration (57 ms), Drieghe and Brysbaert (2002) found phonological priming effects along with a comparable semantic priming effect (associate vs. control). Both pseudohomophones and homophones of the associate facilitated lexical decision response times. At the longer prime duration (253 ms), the homophone priming effect disappeared but a reliable pseudohomophone effect remained. This is basically consistent with Van Orden's claim of a later orthographic verification phase that is limited to a check of known orthographic patterns. The Drieghe and Brysbaert (2002) data suggest that initial activation of addressed phonological forms can be generally suppressed to fulfill task demands, but strategic homophone inhibition occurs at a later stage. Consistent pseudohomophone priming demonstrates early, mandatory, and automatic processing of phonological codes even when a spoken response is not required. Thus, it seems unlikely that phonological processing in isolated word recognition is driven by post lexical access production processes, as the dual route cascade (DRC) model claims (Coltheart et al., 2001).

Eye Movement Experiments

Eye movement experiments have also used homophones and pseudohomophones to examine the role of phonology. In these studies, eye movements are monitored while skilled readers silently read target words embedded in meaningful sentences. Eye movements are an online measure of the cognitive processes used during natural reading, and fixation durations are more sensitive to processing demands than are manual response times (Rayner, 1998). Many eye movement experiments have demonstrated the activation of phonological codes during the silent reading of text (Folk, 1999; Folk & Morris, 1995; Pollatsek, Lesch, Morris & Rayner, 1992; Rayner, Sereno, Lesch, & Pollatsek, 1995).

Folk (1999) tapped the potential semantic ambiguity of homophones to examine phonological processing in reading. Two experiments manipulated meaning dominance and lexical frequency by presenting balanced homophone pairs (i.e. two similarly frequent meanings) and biased homophone pairs (i.e., one dominant meaning). Each homophone could appear in either a correct sentence context (e.g., Sally asked for a *piece* of cherry pie.) or an incorrect context (e.g., The tribe was reluctant to sign a *piece* treaty.) Folk found longer reading times on correctly used homophones (*piece/peace*) relative to control words with comparable lexical frequency. Folk's data suggest that phonological codes activated both potential meanings for the balanced high frequency and low frequency word pairs. This result indicates that orthographic information alone was not sufficient to suppress competition among the multiple meanings evoked by accessing a word's phonological form during silent reading.

Another advantage of eye movement technology is the ability to unobtrusively control what text readers are seeing and when they are seeing it. Readers perceive a surprising amount of information during a fixation. In addition to seeing the fixated word in foveal view, readers also extract parafoveal information about the next word (Dodge, 1907). The boundary-change technology pioneered by Rayner (1975) allows the experimenter to manipulate what the reader sees. Parafoveal preview is one type of boundary-change technique illustrated in Figure 2. Such experiments control what information the reader gets from an upcoming word before the eyes actually land on it. Initially, a preview stimulus appears in the sentence instead of the target word. While fixating on the word before the preview (*were* in the example), readers begin to process the preview stimulus (*floan*) parafoveally. When readers move their eyes to fixate the target word location, the eyes cross an invisible boundary and trigger a change that displays the target (*flown*). Because the preview information is not processed consciously and is replaced by the target word during a saccade, when vision is suppressed, readers are not aware of the change in the display. Preview experiments manipulate the characteristics of the preview and/or the relationship of the preview to the target. The preview might share semantic, phonological, or orthographic characteristics with the target depending on the experimental question at hand. Shorter fixation times in the related condition show that the preview facilitated recognition of the target and suggest that the shared characteristic contributes to word recognition. Such experiments have demonstrated that phonological codes and "abstract letter identities" are perceived parafoveally and affect target word identification, but actual letters are not preserved across saccades (Rayner, 1998; Liversedge & Findlay, 2000).

Figure 2. The Parafoveal Preview Technique

The asterisk (*) marks the fixation point. The invisible boundary that triggers the display change is indicated by the pipe(|).

```
                 *  |
The exotic pets were floan in from South America.
                    | *
The exotic pets were flown in from South America.
```

Pollatsek et al. (1992) used the parafoveal preview technique to establish that homophone previews facilitated reading times relative to a parafoveally presented non-homophone control. For example, the target word *rains* (presented in non-italicized, lower case and embedded in a sentence context) was read faster when preceded by its homophonic preview (*reins*) than an orthographic control preview (*ruins*). Recently, Miellet and Sparrow (2004) demonstrated phonological priming effects in an experiment with pseudohomophone previews in French. Unlike homophone previews, for which the phonological representation is addressed in the lexicon, pseudohomophone previews are novel letter strings that have no existing orthographic-semantic associations. High and low frequency words were presented in sentence contexts preceded by a parafoveal preview that was either the identical word, a pseudohomophone (e.g., *roze* in English) or a nonword control (e.g., *roke*). First-pass fixation times on high and low frequency words were comparable for the identical and the pseudohomophone conditions, and significantly longer for the nonword controls. Frequency affected fixation durations in the identical preview condition (e.g., a real word), but not in either of the two nonword preview conditions. Together, the data from Pollatsek et al. (1992) and Miellet and Sparrow (2004) indicate that skilled readers use phonological processing in the early identification of high and low frequency words during silent reading.

The fast-priming paradigm (Sereno & Rayner, 1992) is another type of display change technique used to study the time course of phonological and orthographic processing. In the fast priming paradigm, the reader cannot see the upcoming target word (n+1) until it is actually fixated. Before this time, a string of x's or random letters holds the place of the target word, eliminating any parafoveal preview. As the eyes move to fixate on the target word, they cross a boundary that triggers the display change. Upon fixation, the string of x's is replaced by a prime which is presented for 18-60 ms before the actual target word appears. The short prime duration suggests that this paradigm taps automatic reading processes that are not consciously controlled by the reader.

Rayner et al. (1995) used the fast-priming technique and found priming effects from pseudohomophone primes that were comparable in size to homophone priming effects. However, later fast-priming experiments did not replicate the pseudohomophone priming effects (Lee, Kim, Binder, Pollatsek, & Rayner, 1999). In a separate study Lee et al. (1999) presented a homophone (*beach*) or a visually similar control (*bench*) for a variable duration before the target word (*beech*) appeared. Phonological priming from the homophone appeared with the 29 ms and 35 ms prime durations, but not with longer prime durations. Orthographic priming from the visually similar word appeared at those durations and also later (up to 41 ms). The Lee et al. findings are consistent with an early orthographic/ phonological processing stage followed by a second orthographic verification phase.

Collectively, eye movement experiments have consistently found evidence of pre-lexical phonological processes operating at the letter/phoneme level in reading, irrespective of which display change paradigm was used.

Homophone effects in non-alphabetic writing systems. In alphabetic writing systems such as English, most sounds require a particular letter for their spelling. For example, there is no way to spell /b/ without a *b* or /d/ without a *d*. Because virtually all homophones have letters in common as well as sounds, it is difficult to determine whether homophone and pseudohomophone effects are truly phonological in nature and not due to orthographic overlap. In non-alphabetic writing systems, however, many syllables are homophonic and can be written with visually dissimilar characters.

Eye movement studies in Chinese have established that phonological codes are processed parafoveally in word recognition. Pollatsek, Tan, and Rayner (2000) found that naming latencies were shorter when targets were preceded by visually dissimilar homophonic previews than by nonhomophone controls that did not share the phonetic radical of the target. Liu, Inhoff, Ye, and Wu (2002) measured fixation durations while participants silently read targets embedded in sentence contexts. They found shorter gaze durations to targets preceded by homophonic previews and visually similar previews that shared the phonetic radical of the target. Tsai, Lee, Tzeng, Hung, and Yen (2004) conducted an eye movement study that found evidence for parafoveal phonological processing of homophone targets, when the character was phonologically consistent. In

Japanese Kanji, Wydell, Patterson, and Humphreys (1993) found homophone effects in semantic categorization. Finding homophone effects in writing systems that do not predictably encode phoneme segments indicates that the use of phonological processing in reading is unlikely to be driven by characteristics of the writing system. Rather, it appears that phonological processes are inherent in skilled reading of any language (Perfetti, Zhang & Berent, 1992).

Electrophysiological Studies

The time course of phonological processing has been investigated in several event-related potential (ERP) studies. Early studies often used discrimination type tasks, in which participants made a rhyme judgment about a pair of words, and these studies reported phonological effects that onset as early as 260 ms after target word presentation (Kramer & Donchin, 1987) and peak around 450 ms after word presentation (Rugg, 1984; Rugg & Barrett, 1987). Phonological effects also appeared in experiments using a semantic decision task, in which readers read target words embedded in highly predictable sentence contexts at the terminal position. Newman and Connolly (2004), for example, varied targets with respect to their semantic and phonological appropriateness for the sentence context. In this experiment, a pseudoword that was homophonous with the expected target elicited less negativity (peaking around 400 ms) than a semantically inappropriate word or a nonword that sounded different from the expected target. Hence, most ERP studies to date have examined the role of phonology in word recognition by using experimental tasks that require some conscious judgment from the participant. In such experiments, phonological effects tend to appear in the same time window as semantic effects (i.e., around 400 ms after the target appears).

Although these experiments are informative about phonological processing in highly predictive sentence contexts, their contribution to understanding pre-lexical phonological processing in the course of normal reading is uncertain. For example, it is difficult to reconcile these ERP findings with the time course of word recognition processes suggested by other experimental techniques, such as eye movement and magnetoencephalography (MEG) studies. Eye movement research typically reports word reading times around 250 ms, with somewhat longer fixation durations when parafoveal preview information is not available (Rayner, 1998). Preliminary MEG studies place lexical access around 350 ms post-target (Pylkkänen & Marantz, 2003). Based on the eye movement and MEG data, the phonological effects observed around 400 ms may be more relevant to phonological decision-making or sentence constraint than online phonological processing during word recognition (Kutas & Hillyard, 1984; Kutas & Van Petten, 1990).

Summary of Evidence for Phonological Representations during Reading

The experimental evidence gathered thus far indicates that skilled readers access phonological representations during reading. Homophone effects in naming, lexical decision, semantic categorization, eye movement, and ERP experiments indicate that readers activate addressed phonological codes during isolated word recognition and during silent reading of words in sentences. Pseudohomophone effects, when they occur, suggest that readers also activate phonological representations from novel orthographic strings and use that information to assist word identification. Both homophone and pseudohomophone effects support the claim that phonological representations are activated during skilled reading, but the nature of the phonological representation in reading is not fully understood.

The evidence discussed above is consistent with the strong theory of phonology in word recognition proposed by Frost (1998). This strong view proposes that phonology routinely plays a role in reading for skilled as well as beginning readers. In this way, Frost's strong view of phonology in word recognition contrasts with dual route models that propose that phonological processes are supplementary or subordinate to visual word processing during skilled reading. However, strong phonological theory contends that readers use minimal phonological representations en route to lexical access, which Frost refers to as a *minimality constraint.* According to the minimality constraint, readers use only a sketch of the available phonological information to access a lexical entry, which in turn releases the full phonological form of the word. Therefore, the strong view holds that phonology operates early in word recognition but that early phonological information is incomplete.

If the minimality constraint is correct, it could explain why phonological regularity effects appear inconsistently and usually mainly for low frequency words in lexical decision experiments. If readers do not bother to begin to activate ambiguous vowels before lexical access (such as the one *pint*, which is usually pronounced as in *mint*), then inconsistent regularity effects would not discount a role for early phonological representations. The minimality constraint predicts that if readers activate phonological representations en route to word recognition, these representations will be fundamentally different from spoken language representations until the point of lexical access. The present experiments test two implications of the minimality principle. Initial experiments examine whether early phonological representations contain detailed information about vowel as well as consonant segments. Later experiments investigate whether these early representations contain suprasegmental phonological information.

CHAPTER 3

BACKGROUND AND OVERVIEW OF EXPERIMENTS

Background

Spoken Language Representations

Several linguistic models hold that the phonological representations used in processing spoken language are structured hierarchically and contain multiple layers of sub-lexical information (Selkirk, 1982; Treiman, Fowler, Gross, Berch & Weatherstone, 1995; Frauenfelder & Lahiri, 1989). One example of such a model appears in Figure 3 (taken from Clements & Keyser, 1983). This model depicts multiple levels of phonological representation that includes several layers of sub-lexical information: a prosodic level that indicates the syllable structure; a skeletal level which codes the consonant/vowel pattern; and a melodic level that represents the contrasting properties of speech sounds. It is possible that the phonological representations in reading are similarly rich (Liberman et al., 1989).

Figure 3. Phonological Representation in Spoken Language

Word:			CANDY		
Prosodic level (suprasegmental)		σ			σ
Skeletal level (segment)	C	V	C	C	V
Melodic level (features)	[k	ae	n	d	i]

During silent reading, skilled readers might represent the available phonological information in multiple levels of activation, similar to the representations used in spoken language. Alternatively, they might use a simplified, minimal representations that do not specify all of the available phonological information. As I discussed in the previous chapter, Frost's (1998) minimality principle holds that the phonological representations formed early in word recognition do not include the elaborated, linguistic information described above.

Currently, most reading researchers conceive of phonological representations as containing phoneme segment information. This conception is a central premise for advocates of early, direct phonics instruction, as phoneme segments generally correspond with the orthographic information available from print (e.g., *dog* and its phonological form). In contrast, suprasegmental information about a word's phonology, such as onset-rime, syllable boundary, or lexical stress pattern, is not explicitly encoded in English orthography and would be difficult to represent in a linear string of phoneme segments. The previous literature is consistent with the present assumption that skilled readers use simplified, linear, phonological representations. Such a representation might offer back-up phonological support to a visual lexical access route, and the supplemental nature of that representation might entail minimal content to support efficient processing. Huey (1908) concluded that "... while this inner speech is but an abbreviated and reduced form of the speech of everyday life, a shadow copy as it were, it nevertheless retains the essential characteristics of the original" (p.123). The present research asks *what* that essential information entails. The subjective experience of inner speech is that it includes intonation contours and other prosodic elements. This suggests the possibility that skilled readers activate elaborated phonological representations that include suprasegmental as well as segmental information. Thus, the past and current assumptions about phonological representation in reading invite further investigation of whether readers construct speech-like phonological representations en route to word identification or use a minimal subset of phonological information to access the lexical form.

Previous Research about the Nature of Phonological Representations in Reading

Although the homophone and pseudohomophone data discussed previously indicate that readers represent phonological information during reading, these experiments say little about the nature of that representation. At the present time, few researchers have applied the phonological principles of spoken English to investigate the nature of the phonological representations in written language. Among those who have, some examined the grain-size of phonological information represented whereas others sought evidence of a hierarchically structured representation of written language.

Do phonological representations have detailed content? A question remains as to whether prelexical phonological processing uses only a limited amount of the available information (i.e., a "good enough" representation) for lexical access, or whether it uses all of the information available from an upcoming word. The following experiments asked whether detailed phonetic information is represented during reading. Birch, Pollatsek, and Kingston (1998) examined the extent to which phonemic and phonetic codes are activated during word recognition. In a phonological lexical decision task (i.e., does it sound like a word?), participants accepted phonetic pseudohomophones (*nootle*) as sounding like real words in 78% of the trials, whereas deletion controls (*sootle)* were accepted in only 13% of the trials. Phonemic pseudohomophones (*awaik*) were judged to sound like real words on 96% of the trials. In a traditional lexical decision task (i.e., is it a word?), participants made more errors and took longer to reject phonetic and phonemic homophones (*nootle* & *awaik*) as compared to deletion controls (*sootle*). In this experiment, the size of the pseudohomophone effect was not significantly different when the materials were phonetically and phonemically similar, as compared to when the materials were only phonemically similar. Based on the above data, Birch et al. (1998) concluded that phonemic codes were activated in the classic lexical decision task but phonetic codes were not. This suggests that word identification in lexical decision does not activate a detailed phonetic representation of the target.

A recent lexical decision study suggests that vowel duration, as well as vowel identity, is included in the phonological representations used during lexical decision. Lukatela, Eaton, Sabadini, and Turvey (2004) replicated a vowel lengthening effect first reported by Abramson and Goldinger (1997). *Vowel lengthening* refers to the observation that the pronunciation duration of orthographically identical vowels is affected by whether the following consonant is voiced (e.g., /b/, /d/, /m/) or unvoiced (e.g., /k/, /p/, /t/), such that longer vowel durations precede a voiced consonant. For example, the vowel duration in *slid* is longer than the vowel duration in *slip*. In a series of lexical decision experiments, Lukatela et al. (2004) found longer lexical decision times to words pronounced with longer vowel durations (*slid*), than words with shorter vowel durations (*slip*). As the vowel lengthening effect withstands interference from concurrent articulation, these data indicate that gestural information about phoneme duration is not part of the immediate articulatory plan. Thus, it may be part of a word's abstract phonological representation.

The data from Lukatela et al. (2004) suggest that detailed gestural information is activated in lexical decision, which suggests that the phonological representations activated in lexical decision may be like those used in spoken language. In contrast, Birch et al. (1998) concluded that the phonological representations in word recognition are not as detailed as spoken language representations. These studies offer conflicting evidence about the nature of the phonological representations used in lexical decision, and do not address what phonological information is represented in the course of natural reading.

Do phonological representations contain multiple levels of sub-lexical information? Caramazza and Miceli (1990) noted that distinct error patterns emerged in the spelling of stroke patients, such that patients were differentially successful in retrieving correct consonants than correct vowels. These clinical observations motivated their initial proposal that written language representations may be hierarchically structured. Particularly, Caramazza and Miceli suggested that graphemic representations used in writing contain skeletal information that categorically distinguishes between consonants and vowels (see the skeletal level in Figure 3).

A few previous experiments have examined whether phonological representations include vowel and consonant category information. Berent and Perfetti (1995) examined vowel processing in early word recognition using a backward masking paradigm, and their experiments found evidence for separate time courses for consonant and vowel processing. Participants were presented with target words at brief durations (15 ms, 30 ms, 45 ms, 60 ms) followed by a nonword backward mask that preserved the first letter of the target along with either the remaining consonant or the vowel information in the target. For example, the target *rake* was followed by either a consonant-preserving mask (*RIKK*) or a vowel-preserving mask (*RAIB*). The experiments varied the mask duration as well as target word duration, and recorded participant accuracy at reporting the targets. Berent and Perfetti (1995) found that the consonant-preserving mask resulted in more accurate identification of the target than the vowel-preserving mask in the shorter presentation conditions. This result suggests that readers resolve consonant information earlier than vowel information when they are identifying single words. This is known as the *two-cycles theory* (Berent & Perfetti, 1995). Subsequent studies raised doubts about the validity of the backward-masking procedure, however (Brysbaert, Praet, & d'Ydewalle, 1990; Lukatela & Turvey, 2000; Perry & Ziegler, 2002). These researchers were concerned that such short exposure durations encouraged strategic guessing, rather than automatic word recognition processes.

Two eye movement experiments essentially replicated the Berent and Perfetti (1995) two-cycles effect in word recognition during silent reading. Lee, Rayner, and Pollatsek (2001, 2002) used a fast-priming paradigm to withhold either consonant or vowel information early in a fixation for words embedded in sentence contexts. They reported that delaying consonant information by 30 ms resulted in longer fixation durations compared to the no-delay condition, whereas delaying vowel information did not. Lee et al. (2001, 2002) concluded that this difference between consonant and vowel processing might emerge from the characteristics of written English, rather than from categorical distinctions between consonants and vowels in phonological representations. It is noteworthy that two-cycle effects were not observed in languages with more regular vowels, such as Italian (Colombo, Zorzi, Cubelli, & Brivio, 2003).

Two other recent eye movement studies investigated whether skilled readers represent suprasegmental phonological information during silent reading (Ashby & Rayner, 2004; Ashby & Clifton, 2005). Ashby and Rayner (2004) used eye-contingent display change techniques to present readers with a partial word prime (foveally or parafoveally) containing either the first two or three letters of the target. For half of the targets, the two-letter prime constituted the exact first syllable, whereas the three-letter prime constituted the exact first syllable for the other targets. In the parafoveal preview experiment, Ashby and Rayner (2004) found that targets were read more quickly when preceded by a preview that was identical to its first syllable, as compared to previews that had one more letter or one less letter. These data suggest that readers can include at least the initial syllable in the early phonological representations that begin with parafoveal information, and use that information to facilitate word recognition. Unfortunately, the data were not as clear in Ashby and Rayner's (2004) other experiment, which presented foveal primes in a fast-priming paradigm (Sereno & Rayner, 1992). Ashby and Clifton (2005) examined whether the prosodic property of lexical stress would affect fixation durations. Pairs of high and low frequency words with one stressed syllable (*significant*) and two stressed syllables (*fundamental*) were embedded in sentence contexts. Whole word pronunciation durations and peak intensity measures for each syllable confirmed the stress categorization of each word. Participants silently read target words with one or two stressed syllables embedded in sentence contexts, seeing one member of the pair or the other in a given sentence. Members of each pair were matched for number of letters, number of syllables, frequency, and morphological structure. Ashby and Clifton (2005) found that words with two stressed syllables were read more slowly and received more first-pass fixations on average than words with one stressed syllable. Thus, it appears that lexical stress assignment may be a late phase of word recognition that affects eye movement control. Together, Ashby and Rayner (2004) and Ashby and Clifton (2005) offer preliminary evidence that readers represent suprasegmental phonological properties during silent reading. These findings suggest that skilled readers activate elaborated phonological representations, and the present experiments further test this idea.

Overview of Experiments

The present experiments investigate whether skilled readers use elaborated or minimal phonological representations in silent reading by examining what aspects of the available phonological information influence word recognition. For example, evidence of minimal early representations might include incomplete segment information. Evidence of full representation of segmental information would indicate that the essential minimal elements readers represent are phonological segments, but does not indicate whether these representations also include suprasegmental information. Evidence of the early representation of syllable information would suggest that readers activate elaborated, speech-like phonological representations early in word recognition. A deeper understanding of phonological representation in reading should further our understanding of the cognitive interface between spoken language and reading processes as well as offer an empirical base for a descriptive theory of phonological representation in reading that is coherent with the current understanding of phonological processing in spoken language.

Chapter 4 presents two eye movement experiments that investigate what segmental phonological characteristics get represented parafoveally and influence word recognition processes. Experiments 1 and 2 examine how readers process vowels parafoveally. Chapter 5 reports two eye movement experiments that examine the parafoveal processing of syllable information in lexical decision and sentence reading (Experiments 3 & 4). Chapter 6 presents Experiment 5, which records event-related potentials (ERPs) during single word reading in a masked-priming paradigm to investigate the link between multi-level phonological representations and memory proposed in Ashby and Rayner (2004).

In combination, the five experiments test two hypotheses about the nature of phonological representations in word recognition during silent reading. The first hypothesis asserts that skilled readers routinely construct elaborated, speech-like phonological representations during silent reading. These representations include suprasegmental information about syllabic constituents of a word as well as relatively complete segmental information. The second hypothesis asserts that readers use these representations to initiate and maintain a memory store of phonological information that can be used to support comprehension processes.

If these experiments find that readers activate elaborated phonological representations with a similar linguistic content as the representations used in spoken language, then this would suggest that word recognition during silent reading utilizes the phonological representations of spoken language, following the assumption of parsimony. Thus, finding such similarity would be inconsistent with the distinct pathways model described in Chapter 1. Alternatively, these experiments may find that the phonological representations in early word recognition are minimal and unidimensional or do not contain detailed phonological information. This would indicate that the representations used in word recognition differ substantially from those used in spoken language, consistent with the distinct pathways model described in Chapter 1.

CHAPTER 4

THE REPRESENTATION OF VOWELS DURING SILENT READING

Experiments 1 and 2 address the question of whether the pre-lexical phonological representations used during silent reading contain detailed phonological information or a minimal sketch of phonological information. This idea is formalized in the *minimality principle* (Frost, 1998), which states that the representation used for lexical access contains the minimum amount of phonological information that is necessary to activate a unique lexical item. As consonants are much less variable than vowels in their sound-spelling relationships in English, they carry more reliable information than vowels. It is conceivable that the pre-lexical representations used in word recognition consist primarily of consonant information. Frost (1998) and Shimron (1993) noted that certain ambiguous vowel phonemes, such as the vowel in *pint*, need not be resolved in order to activate a particular lexical item. Thus, one test of the minimality principle is whether vowel information is included in pre-lexical phonological representations.

How vowels are processed during reading is not obvious. In English, a given vowel spelling can correspond to several potential phonemes (e.g., *a* as in *tack* and *spa*, *ou* as in *shout* and *soup*); vowels are more variable in their spelling–sound relationships than consonants (Kessler & Treiman, 2001). The inconsistency of vowels is thought to impact their role in early word recognition (Brown & Besner, 1987; Carr & Pollatsek, 1985; Perfetti & McCutchen, 1982), making them more difficult to process than consonants. That is, vowel and consonant information may participate in word recognition in different ways.

When reading text silently, readers often begin to identify an upcoming word before the eyes actually look at it. Several eye movement experiments indicate that parafoveally acquired phonological information plays a significant role in skilled reading (Chace, Rayner, & Well, 2005; Henderson, Dixon, Petersen, Twilley, & Ferreira, 1995; Lesch & Pollatsek, 1998; Pollatsek et al., 1992). The results of these studies suggest that readers process lexical phonological codes parafoveally and use that information in word recognition processes that continue in the following fixation. Using a similar boundary change paradigm, Miellet and Sparrow (2004) demonstrated phonological effects with pseudohomophone previews in French. However, because of the inconsistent observation of pseudohomophone effects in the eye movement literature (Lee et al., 1999; Lee, Kambe, Pollatsek, & Rayner, 2005), it is not yet clear whether readers automatically code the phonology of novel letter strings in word recognition.

Given the strong evidence that readers begin to activate phonological information before their eyes actually fixate a word, the present experiments investigated whether these early phonological representations include information about vowels. In each experiment, one condition used a preview in which the vowel phoneme was biased toward the vowel of the target word in a sense to be described. This condition is referred to as the *vowel same* condition. In *the vowel different condition*, in contrast, the vowel phoneme in the preview was biased away from the phonemic vowel of the target word. The experiments differed in the nature of the biasing. In Experiment 1, the preview vowels were orthographically different from the target vowels. The previews in the vowel same condition had vowel spellings that, in the real words of English, generally encoded the same phoneme as in the target vowel. An example is *er* for the target *ir*. The previews in the vowel different condition had vowel spellings that generally encoded a different phoneme from the target vowel, such as *or* for the target *ir*. The question at hand was whether the target words would be read more quickly in the vowel same condition than the vowel different condition. If so, this would suggest that readers computed phonological vowel information on the basis of the parafoveal input and that this information affected their later processing of the target word. In Experiment 2, I used vowel spellings such as *ea* and *oo*. The preview vowel and the target vowel had the same spelling. These spellings, unlike the majority of those in Experiment 1, encoded more than one possible phoneme. For example, *oo* is sometimes pronounced as /u/ as in *loon* and sometimes as /ʊ/ as in *cook*, with /u/ being the more common pronunciation. The phonemic vowel of the preview was biased by its following consonant either toward or away from the target's phonemic vowel. For example, the target *drool* was preceded by the preview *droon* in the vowel same condition or *drook* in the vowel different condition. Based on the statistics of English, a following *k* conditions the vowel phoneme such that it is usually pronounced as /ʊ/. That is, the final consonant should bias the vowel phoneme in the preview away from the target's vowel phoneme. If the target words are read more quickly in the vowel same condition than in the vowel different condition, this would suggest that vowel information was included in the representation that was formed on the basis of parafoveal input and that this information was affected by the consonantal context in which the vowel appeared. Together, the results of these experiments should shed light on whether readers begin representing phonological vowel segments based on parafoveal input, whether this information is affected by the consonantal context in which the vowel appears, and whether these early phonological representations facilitate word recognition during silent reading.

Experiment 1

Experiment 1 examined whether readers process vowel segment information parafoveally and use it to facilitate word recognition. Targets (e.g., *chirp*) were preceded by nonword previews whose vowel spellings most commonly represent the same vowel phoneme (*cherg*) or a different vowel phoneme (*chorg*) from that of the target. In neither condition were the preview vowels spelled the same as the target vowels. If skilled readers begin to assign phonological vowel information before the target is fixated, then targets preceded by vowel-same previews should be read faster than targets preceded by vowel-different previews. It is possible, however, that orthographic processing mediates the effect of vowel-same previews, such that detection of an orthographic mismatch between the preview and the target results in rejecting the phonological code of the preview. In that case, the lack of full orthographic overlap between the target and previews could prevent readers from using the phonological preview information to facilitate word recognition, and the fixation times in the two conditions should not differ.

Methods

Participants. Thirty-eight students at the University of Massachusetts were paid or received experimental credit to participate in the experiment. All participants were native English speakers with normal vision who were naive about the purpose of the experiment.

Apparatus and procedure. The stimuli were presented on a NEC 4FG monitor through a VGA video board that was controlled by a personal computer with a 486 processor. An analog-to-digital converter interfaced the computer with a Fourward Technologies Generation VI Dual Purkinje Eyetracker. The monitor displayed text at a 200Hz refresh rate that permitted display changes within 5 ms. The eyetracker monitored movements of the right eye, although viewing was binocular. Letters were formed from a 7 x 8 array of pixels, using the fixed-pitch Borland C default font. Participants sat 61 cm away from a computer screen and silently read single-line sentences while head position was stabilized by a bite bar. At this viewing distance, 3.8 letters occupied one degree of visual angle. At the beginning of the experiment, the eye-tracking system was calibrated for the participant. At the start of each trial, a check calibration screen appeared, and participants who showed a discrepancy between where their eye fixated and the location of the calibration squares were re-calibrated before the next trial.

On each trial, the check calibration screen appeared and the experimenter determined that the eye tracker was correctly calibrated. The participant was instructed to look at the calibration square on the far left of the screen, then the experimenter presented the sentence. When the sentence appeared on the screen, a nonword preview appeared in the target region. As readers read the sentence and their eyes approached the target region, this preview appeared parafoveally in their field of vision. Presentation of the actual target word was triggered during reading by a saccade into the target region, as the eyes crossed an invisible boundary placed after the last letter of the preceding word (see Figure 2). When the participant finished reading the sentence, he or she clicked a response key to make it disappear. Following a quarter of the trials, a comprehension question appeared on the screen. The participant responded by pressing the response key that corresponded with the position of the correct answer. Then the check calibration screen appeared before the next trial. The experiment was completed in one session of approximately 30 minutes.

Materials. Thirty-four target words were embedded in single-line sentences (see Appendix A). The target words were monosyllables between four and six letters in length with a mean standard frequency index (SFI) of 49.3 (Zeno, Ivens, Millard, & Duvvuri, 1995). Target words were preceded by a pronounceable nonword preview in which the vowel phoneme was either the same as or different from the vowel phoneme in the target. For example, the target *dawn* had one of two previews: *daik* (in the vowel-different condition) and *dauk* (in the vowel-same condition). The expected pronunciation of the vowel-different and vowel-same previews was confirmed by determining what proportion of one-syllable words with that rime pattern are pronounced with the same phonemic vowel as the target (.013 and .804, respectively). Word counts were weighted by SFI rating (Zeno et al., 1995). Both previews had the same initial letter as the target word as well as a common last letter that differed from the target. Nonword previews were typically constructed by substituting two of the letters at the end of the target word. According to the Mayzner and Tresselt (1965) position-specific letter frequency ratings, the previews in the same and different conditions had comparable vowel bigram frequencies (42.7 and 41.4 per million words, respectively) and roughly comparable final trigram frequencies (0.7 and 1.1 per million words). The mean final trigram frequency for the target words was 6.8 occurrences per million words.

Design. Each participant read every target word once, with each target preceded by one of the two possible nonword previews. Experimental condition was defined by the type of preview (vowel-different or vowel-same). Each participant read the 34 experimental sentences randomly interspersed with 96 unrelated filler items that also included a parafoveal preview display change.

Results and Discussion

Fixation time on the target word was the dependent variable, and preview type was treated as a within factor in both the participant and item analyses. First fixation duration, single fixation duration, and gaze duration are the three fixation time measures reported, since these are most clearly influenced by word recognition processes (Rayner, 1998). *First fixation duration* is a measure of the mean time spent reading the first time the eye lands on the target word and does not include skips. First fixation is a complete measure of reading time for words read in a single fixation, but it is only a partial measure of reading time for words that received multiple fixations. *Single fixation duration* is the mean time spent reading targets that received only one fixation. *Gaze duration* is a cumulative measure of the mean time spent reading before the eyes move away from the target, irrespective of the number of fixations made while on the target. Other measures such as probability of fixation, spillover, and proportion of regressions are not reported, as they revealed no significant differences between conditions.

Consistent with most eye movement research (Rayner, 1998), the data were trimmed to eliminate overly short and long fixations. Fixations under 80 ms were eliminated since such short fixations do not seem to reflect cognitive processing of the target word (Rayner, 1998; Rayner & Pollatsek, 1987). Fixations over 550 ms were also eliminated, and approximately 6% of the full data set (i.e., target words and sentence contexts) was lost for these reasons. Trials were excluded from the analyses for three reasons: if no fixations were made on the target word before the eyes moved past it to the right, if the reader blinked while within the target region, or if the display change occurred before the eyes landed in the target region. Participants for whom 75% of the data were retained after these exclusions and who answered more than 80% of the comprehension questions correctly were included in our data set. This data criterion is similar to that used in other display change experiments in which there are several reasons for data loss (Sereno & Rayner, 1992), and it resulted in the exclusion of three participants from the Experiment 1 analyses. Analyses of variance (ANOVA) by participants (F_1) and items (F_2) were restricted to trials in which the saccade into the target region was launched within seven characters from the initial letter of the target, which is close to the average length of saccades during reading (Rayner, 1998). This excluded trials in which the launch site of the saccade into the target region was far enough away to hinder parafoveal processing of the critical letters in the preview (Rayner, McConkie, & Zola, 1980; Rayner, Well, Pollatsek, & Bertera, 1982). A similar number of data points contributed to each condition in the participants and items analyses.

First fixation duration. Table 1 shows the mean first fixation times for target words preceded by previews with vowel phonemes that were different from or the same as the vowel phoneme in the target. First fixation durations were 7 ms shorter on average for targets preceded by vowel-same previews than by vowel-different previews, but this effect was not significant, $F_1(1, 37) = 3.19, p < .10$; $F_2(1, 33) = 3.40, p < .10$.

Single fixation duration. The mean single fixation times for target words preceded by vowel-different and vowel-same nonword previews appear in Table 1. Single fixation durations were 9 ms shorter on average for targets in the vowel-same condition than the vowel-different condition, $F_1(1, 37) = 5.23, p < .05$; $F_2(1, 33) = 5.71, p < .05$.

Gaze duration. The mean gaze durations for target words preceded by vowel-different and vowel-same previews appear in Table 1. Gaze durations were 15 ms shorter on average for targets preceded by vowel-same previews, as compared to the vowel-different condition, $F_1(1, 37) = 6.15, p < .05$; $F_2(1, 33) = 5.25, p < .05$.

Table 1. Reading Time (ms) for Target Words in Experiment 1

	Vowel-Different Preview	Vowel-Same Preview
First Fixation	296	289
Single Fixation	305	296
Gaze Duration	324	309

In summary, participants spent less time reading target words preceded by vowel-same previews than by vowel-different previews. These results suggest that readers began activating the phonemic vowel in the next saccade target parafoveally and integrated this representation with the foveal information available during subsequent fixations to read the target word. Because the vowel letters in both preview conditions differed from those of the target, the data demonstrate a phonological vowel effect in the absence of complete orthographic overlap.

One could counter that the results we obtained are due to some type of low-level visual similarity effect. The letters in the vowel-same condition previews may have been more visually similar to the target than the letters in the different-vowel-bias condition previews. For example, the *e* in *cherg* could be more similar to the *i* in the target *chirp* than is the *o* in *chorg*. However, an influence of visual similarity seems unlikely. Previous eye movement research has found that changing letter case between parafoveal and foveal presentations of a word does not affect reading times, suggesting that visual letter forms are not integrated across saccades during reading (McConkie & Zola, 1979; Rayner et al., 1980). Nonetheless, Experiment 2 addressed the possible confound of visual letter similarity by using nonword previews with orthographic vowels that were identical to the target vowel.

Experiment 2

The results of Experiment 1 suggest that, by the time readers fixate a given word, some information about phonological vowels is already activated and included in the developing phonological representation. Experiment 2 investigates *how* readers process phonological vowels. Specifically, I asked whether the phonological representation of an ambiguous vowel is influenced by its following consonant. This question is of interest because studies of English spelling-to-sound relationships show that the pronunciations of vowels become more consistent when the vowel is considered in the context of the surrounding consonants (Kessler & Treiman, 2001; Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995). The consonant(s) that follow the vowel are particularly influential, consistent with the view that vowel + final consonant units or *rimes* have a special role in English (Treiman & Kessler, 1995). For example, the vowel *a* is somewhat inconsistent in terms of spelling-to-sound translation, as it can be pronounced as in *rack*, *spa*, or *hall*. However, this vowel is pronounced consistently as /ɔ/ when followed by *ll*, as in *hall, call,* and *small*. Studies by Treiman, Kessler, and Bick (2002; 2003) have demonstrated that adults' nonword reading and spelling is influenced by the contextual dependencies documented in the Kessler and Treiman (2001) corpus analyses. Although adults do not always pronounce a vowel like *a* as /ɔ/ when it occurs before *ll*, they are more likely to pronounce it this way before *ll* than before *ff*.

Do readers use consonant information to bias the parafoveal processing of vowels in silent reading? To address this question, Experiment 2 used identical vowel letters in the preview conditions and the target words. Targets (e.g., *rack*) were either preceded by nonword previews in which consonantal context was expected to lead to relatively substantial activation of a vowel phoneme that differed from that of the target (e.g., *rall*), or previews (e.g., *raff*) in which the most highly activated vowel phoneme was expected to match that of the target, with little or no activation of an alternative vowel. If readers are sensitive to the conditional consistencies reported by Kessler and Treiman (2001) and if they use consonant information early in word recognition to guide their activation of vowels, then we would expect to find shorter fixation times on targets in the vowel-same condition than in the vowel-different condition. If readers cannot integrate parafoveal consonant and vowel information or if they do not use conditional consistencies, no difference should appear between the two conditions in fixation times. In this scenario, word recognition might proceed in several ways. Readers could initially activate several competing vowel options, as in Lesch and Pollatsek (1998), or they could activate the vowel phoneme that is most commonly represented by the letter pattern. Alternatively, readers could use a placeholder until lexical access specifies the vowel phoneme, in line with the minimality hypothesis.

Methods

Participants. Forty-two students from the same population as Experiment 1 participated. None of the participants were included in Experiment 1.

Apparatus and procedure. The same apparatus and procedure were used as in Experiment 1.

Materials. Thirty-two target words were embedded in single-line sentences (see Appendix B). Target words had four different vowel spellings (*ea*, *oo*, *o*, and *a*), and ranged in length from four to six letters, with a mean standard frequency index (SFI) of 49.2 (Zeno et al., 1995). Targets were preceded by a preview in which the coda consonant strongly conditioned the vowel pronunciation. For example, the target *rack* had one of two previews: *rall* (the vowel-different condition) and *raff* (the vowel-same condition). The expected pronunciation of the vowel-different and vowel-same previews was confirmed by determining what proportion of one-syllable words with that rime pattern are pronounced with the same phonemic vowel as the target (.153 and 1.000, respectively). Word counts were weighted by SFI rating (Zeno et al., 1995).

Design. The design was the same as in Experiment 1 except that each participant read the 32 experimental sentences randomly interspersed with 160 unrelated filler items.

Results and Discussion

Fixation time on the target was the dependent variable, and preview type (vowel-different or vowel-same) was treated as a within factor in both the participant and item analyses. The data were trimmed following the same procedures as in Experiment 1. As in Experiment 1, no significant differences were found between conditions on probability of fixation, spillover, and proportion of regressions, and so these variables are not discussed further.

First fixation duration. The mean first fixation times for targets preceded by vowel-different and vowel-same nonword previews appear in Table 2. First fixation durations were 19 ms shorter on average for targets preceded by vowel-same previews than for targets preceded by vowel-different previews, $F_1(1, 41) = 5.98, p < .05$; $F_2(1, 31) = 4.04, p = .053$.

Single fixation duration. Table 2 shows the mean single fixation times. Single fixation durations were 16 ms shorter on average for targets preceded by vowel-same previews than for those preceded by vowel-different previews; the effect was marginal in the participants analysis, $F_1(1, 41) = 3.42, p = .07$, and significant in the items analysis, $F_2(1, 31) = 4.46, p < .05$.

Gaze duration. The mean gaze durations for target words appear in Table 2. Gaze durations were 19 ms shorter on average for targets preceded by vowel-same previews than for targets preceded by vowel-different previews. $F_1(1, 41) = 5.26, p < .05$; $F_2(1, 31) = 4.94, p < .05$.

Table 2. Reading Time (ms) for Target Words in Experiment 2

	Vowel-Different Preview	Vowel-Same Preview
First Fixation	304	285
Single Fixation	311	295
Gaze Duration	330	311

The advantage observed for the vowel-same preview over the vowel-different preview suggests that the consonant information in the preview biased readers' early representation of the vowel phoneme. The advantage observed for the vowel-same preview over the vowel-different preview suggests that the consonant information in the preview biased readers' early representation of the vowel phoneme. In the case of *drook*, for example, activation of /u/ appeared weaker than in the case of *droon*. Less activation of /u/ in the different condition, and more activation of the context-conditioned pronunciation /ʊ/, would have led to the slower processing of targets preceded by discordant previews. Longer reading times in the different condition could also indicate activation of a single vowel phoneme that differs from that in the target or the activation of multiple alternative phonemes. The present data cannot distinguish between these alternatives. However, if the final consonant information had not biased vowel processing, then readers should have represented the dominant vowel, /u/, to an equal degree for both *drook* and *droon*. In this case, no differences in fixation time between the two conditions would have appeared. The observed fixation duration differences thus suggest that readers used the final consonant to guide vowel processing toward the typical phoneme in *droon* and toward the less common consonant-conditioned phoneme in *drook.* This result provides converging evidence for skilled readers' sensitivity to the conditional consistencies established in Kessler and Treiman (2001). Importantly, it provides the first evidence that skilled readers use parafoveal conditional consistencies to inform the early phonological representations that support word recognition during silent reading.

Discussion of Experiments 1 and 2

Two experiments investigated how skilled readers processed vowels when reading silently. The central finding is that skilled readers represented phonological vowels presented in parafoveal previews and used that information in word recognition on the next fixation. The parafoveal previews manipulated the extent to which the vowel phoneme was the same as or different from the vowel phoneme in the target word. Whereas the goal of phonological manipulation was similar in the two experiments, the method of that manipulation differed. In Experiment 1, the vowel phoneme in the previews was manipulated by using different vowel letters than those that appeared in the target word. Here, the letter information from both previews mismatched the foveal letter information. In Experiment 2, the vowel phoneme in the previews was manipulated using the conditional consistencies reported in Kessler and Treiman (2001). Here, the vowel letters in both previews were identical to the vowels letters in the target. In both experiments, skilled readers processed targets faster in the vowel-same preview condition than in the vowel-different preview condition. These results suggest that readers begin to encode vowel phonemes based on parafoveal information and that activation of vowel phonemes is influenced by the consonant that follows the vowel.

One somewhat surprising finding was that the size of the preview effect was nearly as large in Experiment 1 as Experiment 2. In Experiment 1, the foveal letter information conflicted with the parafoveal letter information, yet readers used the parafoveal phonological vowel information anyway. That phonological preview benefits occurred even with conflicting orthographic information in Experiment 1 suggests that inconsistent letter information did not prevent an influence of parafoveal phonological representations on foveal reading times. However, note that vowel effects did not reach significance in the first fixation measure of Experiment 1, perhaps due to the mismatching orthography between the preview and the target.

The present data seem to indicate that readers include vowel phonemes in the early phonological representations constructed on-line during silent reading. Alternatively, one could locate the observed vowel effect in the inconsistency of the mapping from orthography to phonology, rather than in the early phonological representation. Although the vowel letters in Experiment 2 encoded two vowel phonemes, this was not generally the case in the Experiment 1. Therefore, the simplest account of the observed vowel effects appears to be in the early phonological representations readers construct en route to lexical access.

The results of Experiments 1 and 2 are inconsistent with minimality theory, which claims that readers use minimal representations to access lexical items—representations that are often lacking detail about vowels (Frost, 1998; Shimron, 1993). If vowel information were absent from access representations, I should not have observed differences between conditions based on the type of the vowel information that they provide. If readers simply represent the most frequent vowel information early in word recognition, then the preview with the less frequent vowel should not have increased word reading times. The data from the two experiments suggest that readers of English typically use more elaborated phonological representations, which contain information about vowels as well as consonants, in lexical access.

The implication of this data for two-cycles theory (Berent & Perfetti, 1995) is unclear. Although it is possible that consonants were processed more quickly than vowels at an early point in parafoveal word recognition, it appears that readers integrated the two sources of information before the target word is fixated and used this representation in word recognition during the following fixation. If two-cycles theory did hold for parafoveal processing, the quick resolution of parafoveal consonant information might guide the representation of phonologically ambiguous vowels right from the start of word recognition. I expect that any such difference emerges from the relative inconsistency of vowels as compared to consonants in English, rather than from any universal property of linguistic structure.

The result of Experiment 2 offers some insight into the nature of the phonological representations that skilled readers use in lexical access. Accessing the context-conditioned phoneme in the vowel-different preview condition required readers to represent the vowel in the context of the following consonant. When readers fixated the target, however, the following consonant had changed. If the phonemic vowel were only represented in terms of its context, then the changed final consonant should signal readers to abandon that representation, and foveal word recognition could proceed without much interference. In that case, any reading time differences should have been confined to first fixation. The observation of substantially longer reading times in the vowel-different condition suggests that context-based phoneme segment information was accessible even when the context had changed. As readers represented conditioned vowel phonemes with and without their consonant context, our data suggest that several levels of phonological information are used in word recognition. Alternatively, readers initially could use parafoveal consonant contexts to bias the activation of a specific vowel phoneme, which might preserve phoneme information across the saccade to the target.

The observation that nonword previews affected word reading times suggests that skilled readers began to form phonological representations from novel orthographic patterns (e.g., *cherp*) prior to lexical access, on the basis of parafoveally presented information. This result poses several problems for dual-route models of word recognition. The most popular of such models, the DRC, includes only a few grapheme-to-phoneme conversion rules for vowels that are biased by the consonant context (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). For most of the stimuli of Experiment 2, the DRC rules yield the typical context-free pronunciation of the vowel. Another problem for dual-route models relates to their claim that assembly of phonology proceeds serially, whereas addressed phonology involves parallel processing (Coltheart et al., 2001; Havelka & Rastle, 2005). Because dual-route models would consider our nonword previews to be processed along an assembled route, it is not clear how the models could account for the vowel effect observed in Experiment 2. As a serial mechanism would operate from left to right in English, it is difficult to imagine how a letter could bias the pronunciation of the letter to its left. These data also challenge the claim that the assembled phonological route influences word recognition only when a word is sufficiently unfamiliar to prevent lexical access by the faster, addressed phonological route. In both of the present experiments, nonword previews influenced the time spent reading relatively common words, suggesting that readers use phonological information assembled from the parafoveal preview to begin recognizing familiar words.

The vowel effects observed here are more in line with parallel distributed processing (PDP) models of reading that involve cooperative orthographic and phonological processes (e.g., Harm & Seidenberg, 2004). From this perspective, a phonological representation consists of a pattern of phonological activation operating within a semantic space. Although Harm and Seidenberg's (2004) model does not deal with integration of information across fixations, it appears that the model could potentially account for two patterns in the present reading data. In Experiment 1, conflicting parafoveal and foveal letter information did not inhibit readers' use of parafoveal phonological representations in word recognition. Harm and Seidenberg's model predict this result, as simulations indicated that the phonological activation of semantic units appeared stable after masking a visual stimulus, whereas orthographic activation decayed quickly. If the saccade intervening between the onset of parafoveal activation and the activation during target fixation acts as a brief mask, then the primary activation remaining when the target is fixated would be phonological in nature. Additional phonological activation during fixation would continue to drive the system toward the same semantic space, whereas activation from the foveal orthographic information would lag behind. Thus, the model should be able to account for the apparent lack of orthographic gating of the phonological vowel effect in Experiment 1. The major outcome of Experiment 2—that readers were sensitive to dependencies between vowels and final consonants that are relatively common in written English—is consistent with the PDP assumption of frequency-based learning. Readers' acquired sensitivity to orthographic rime patterns could alter the weights of phonological activation so as to yield stronger activation of a vowel phoneme that is less frequent overall when a particular rime pattern is encountered (e.g., *all*). The reading time differences observed in Experiment 2, in particular, require a model that assumes cooperative orthographic and phonological processing.

In summary, these results indicate that skilled readers include vowel information in the early phonological representations used to begin identifying words during silent reading. Parafoveal phonological information facilitated foveal word recognition whether the vowel letters in the preview and target were identical or not. Moreover, when the preview's vowel phoneme was biased by the following consonant, this conditional consistency increased activation of the subordinate vowel phoneme. This is the first demonstration that skilled readers use conditional consistencies to recognize words during silent reading.

CHAPTER 5

THE REPRESENTATION OF SYLLABLES: EVIDENCE FROM SILENT READING AND LEXICAL DECISION

Is suprasegmental phonological information activated in the pre-lexical representations used during silent reading? Experiments 3 and 4 examine whether phonological representations of parafoveally presented letter strings include syllable information, and whether readers use initial-syllable information to help identify the target once it is fixated.

Several experiments in languages other than English indicate that readers process initial-syllable information during word recognition in naming and lexical decision tasks. Perea and Carreiras (1998) demonstrated syllable neighborhood effects on lexical decision and word naming times in Spanish. Carreiras and Perea (2002) found that masked primes of the exact initial syllable facilitated lexical decision more than primes with one more or one less letter. In French, Ferrand and colleagues (2000, 2003) demonstrated that the number of syllables in a word or nonword affected naming and lexical decision latencies. In Chinese, Chen, Lin, and Ferrand (2003) found that naming latencies were facilitated when initial syllables were presented as masked primes, as compared to when masked primes contained tone information alone. Hutzler, Conrad, and Jacobs (2005) conducted naming and lexical decision experiments in German that suggested that words with higher frequency first syllables took longer to recognize than words with lower frequency first syllables.

In English, the evidence for syllabic units in naming experiments has been inconsistent. Ferrand, Segui, and Humphreys (1997) investigated syllable effects in lexical decision and naming using a masked priming paradigm. Primes were presented for 29 ms, preceded by a forward mask and followed by a 15 ms backward mask, before the target word appeared. Primes consisted of either the initial syllable of the target or one letter more or less than the first syllable. In several experiments, participants named targets faster when preceded by primes consisting of the exact initial syllable, relative to primes that contained one letter more or less than the exact initial syllable. Obtaining these data with a brief prime duration (29 ms) suggested to Ferrand et al. (1997) that syllable information was processed early in word recognition. Unfortunately, Ferrand et al.'s (1997) finding that syllable information facilitates word production in English has failed to replicate in experiments conducted by Schiller (1999, 2000).

Ashby and Rayner (2004) conducted the first eye movement experiments to demonstrate that readers can use parafoveally presented syllable information to recognize words during silent reading. However, syllable effects did not appear in another experiment, when primes were presented foveally using the fast-priming paradigm developed by Sereno and Rayner (1992). Ashby and Rayner (2004) attributed the different results in the two experiments to different task demands. For example, in the parafoveal experiment the preview syllable information had to be preserved across the saccade to the target in order to facilitate word recognition, whereas the unmasked foveal prime information did not need to be retained in memory. Since the result of the parafoveal preview experiment has not been replicated yet, it can only be considered a preliminary finding.

Experiments 3 and 4 further investigate whether readers include syllables in the pre-lexical phonological representations used in word recognition during silent reading. Readers in both experiments read target words preceded by two types of parafoveal previews. In the syllable congruent condition, the preview matched the initial syllable of the target exactly. In the syllable incongruent condition, the preview contained one letter more or less than the target's initial syllable. In Experiment 3, target words appeared in sentence contexts and fixation durations were measured in the two conditions. In Experiment 4, parafoveal previews were presented in a boundary-change lexical decision task, and decision times were measured as well as total fixation times on the target. The predictions for these experiments are straightforward. If syllable-congruent previews facilitate word identification time, relative to syllable-incongruent previews, it indicates that readers processed initial-syllable information in the preview and retained it during the saccade to the target word. Evidence of syllable congruency effects would suggest that the early phonological representations in reading contain the suprasegmental phonological information that is included in spoken language representations.

Experiment 3

This experiment attempts to replicate the result of the parafoveal preview experiment reported by Ashby and Rayner (2004). The design of Experiment 3 differs from the original experiment in several ways. The original experiment used both CV and CVC initial target words, whereas the present one uses only CV-initial targets. CV-initial targets constitute the critical test of whether syllable congruency (i.e.. the two-letter prime) facilitates word recognition over and above number of letters (i.e.. the three-letter prime). The original experiment presented the parafoveal preview as letters followed by an underscore, a Greek Pi symbol, and other nonsense characters (e.g.. di_π%#). whereas the present one used only an underscore followed by a consonant string (e.g.. di_zxw). This change was made because of the concern that using characters not usually found in English text had increased readers parafoveal processing time in Ashby and Rayner (2004) and, thus, inflated the observed syllable effect. Experiment 3 also manipulated target word frequency, such that half of the targets were high frequency words and half were low frequency words.

Figure 4. Example materials for Experiment 3

High Frequency
Terry found a good [pos_zxvz or po_zxvxz] *position* in an advertising firm.
Low Frequency
Sally explored the large [bot_zvxzv or bo_zvxvzv] *botanical* garden with interest.

The frequency manipulation was included in order to account for the failure to replicate syllable effects in naming and lexical decision tasks, as reported in Schiller (2000) and Brand, Rey, and Peereman (2003). Several of the Schiller (2000) experiments in English contained high frequency words, whereas the Ferrand et al. (1997) experiments that found syllable effects used mainly lower frequency words. As Jared and Seidenberg (1991) demonstrated that the syllable length effect on naming latency is limited to low frequency words, it seems that syllable-related effects might be more dependably detected by using low frequency materials. This could be because the effect doesn't occur in high frequency words, or because the effect is much smaller than current methods can detect.

Additionally, the Schiller (2000) and Brand et al. (2003) experiments that used Ferrand's original materials exploited different experimental designs, such that each participant saw every target word multiple times in the course of an experiment. It is possible that repeated presentations of low frequency words could give rise to repetition priming effects that obscured any syllable priming that may have occurred. In fact, Ashby and Rayner (2004) used such a design in the parafoveal preview experiment (i.e., every reader saw each target word twice, or once in each preview condition). Reading times were comparable in the syllable congruent and incongruent conditions for the second exposure to the target words, but data from the first presentation indicated congruency effects on mean fixation times. For these reasons, the present experimental design included word frequency as a factor and used single presentations of every target word for each participant.

If readers in Experiment 3 include syllable information in the pre-lexical phonological representations used for word recognition, then mean reading time should be shorter for targets (e.g., *divide*) preceded by two-letter, syllable congruent previews (e.g., di_zvz) than for targets preceded by three-letter, syllable incongruent previews (e.g., div_zv). The distinct pathways view predicts that high frequency words, and possibly the low as well, will be read faster when preceded by the three letter preview, as more letters in the preview would offer greater facilitation when words were recognized through the direct, visual route to the lexicon.

Methods

Participants. Forty-six students at the University of Massachusetts were paid or received experimental credit to participate in the experiment. All participants were native English speakers with normal vision who were naive about the purpose of the experiment.

Apparatus and procedure. The same apparatus and procedure were used as in Experiment 1.

Materials. Sixty-four target words were embedded in single-line sentences (see Appendix C). Half were low frequency words with a mean of 4 occurrences per million words of text and half were higher frequency words with a mean of 217 occurrences per million words of text (Francis & Kucera, 1982). The mean length of the low and the high frequency words was comparable (7.6 letters and 7.4 letters, respectively). Target words (e.g., *botanical*) were preceded by a partial word previews that contained either the first two or the first three letters of the target, followed by an underscore and a consonant string (_zv). The two-letter preview was identical to the initial syllable of the target (bo_ *zvzvzv*), whereas the three-letter preview contained one more letter than the initial syllable (bot_*zvzvx*). The two-letter preview is referred to as *congruent* with the target's first syllable, and the three-letter preview is referred to as the *incongruent* condition. The initial syllables in these high and low frequency words were unstressed and followed by a single consonant. The target words were not predictable from the preceding sentence context.

Design. Each participant read every target word once, with each target preceded by one of its two possible previews. Experimental condition was defined by the type of preview (incongruent or congruent). Each participant read the 64 experimental sentences randomly interspersed with 64 unrelated filler items that also included a parafoveal preview display change.

Fixation time on the target was the dependent variable. Preview type was treated as a within factor in the participant and item analyses. Frequency was treated as a within factor in the participant analyses, and as a between factor in the item analyses. Participant counterbalancing group was included as a between factor in both analyses in order to remove variance due to list (Pollatsek &Well, 1995).

Results

First fixation duration and single fixation duration are the two measures reported. Other measures such as gaze duration and probability of fixation are not reported, as no significant differences appeared between conditions on these measures. The data were prepared for analysis using the same trimming and exclusion criteria as in Experiment 1, with the following exceptions. As a result of the 75% data criterion, eight of the original 54 participants were excluded from the analyses. Analyses of variance (ANOVA) by participants (F_1) and items (F_2) were restricted to trials in which the saccade into the target region was launched within five characters from the target word.[1] This excluded

[1] This is a more restricted launch range than the seven-character range used in Experiments 1 and 2. Mean length of T-1 = 4.5 letters, and the saccade launch probability to T from within that range was 90%.

trials in which the launch site of the saccade into the target region was far enough away to hinder parafoveal processing of the critical letters in the preview (Rayner et al., 1980; Rayner et al., 1982). Less restrictive analyses (e.g., of fixations launched within seven characters of the target region) did not yield any significant differences between conditions. A comparable number of trials were included from each condition in the analyses of the low frequency words and the analyses of the high frequency words.

Table 3. First Fixation Time (ms) for Target Words in Experiment 3

	Incongruent Preview	Congruent Preview	Difference
High Frequency	313	313	0
Low Frequency	335	318	17

First fixation duration. Table 3 presents the mean first fixation times for target words preceded by syllable-incongruent previews and syllable-congruent previews. Readers' initial fixations were 17 ms shorter on average when low frequency targets were preceded syllable-congruent previews than by syllable-incongruent previews. Simple effects tests indicated a significant congruency effect for the low frequency words, $F_1(1,44) = 5.36$, $p < .05$; $F_2(1, 30) = 5.67$, $p < .05$, but not for the high frequency words (F's<1). This interaction between preview congruency and frequency was marginal in the participant analysis, $F_1(1,44) = 2.88$, $p < .10$, and significant by items, $F_2(1, 60) = 4.70$, $p < .05$. The main effect of frequency was significant by participants, $F_1(1,44) = 7.4$, $p < .01$, and marginal in the item analysis, $F_2(1, 60) = 2.13$, $p < .15$.

Table 4. Single Fixation Time (ms) for Target Words in Experiment 3

	Incongruent Preview	Congruent Preview	Difference
High Frequency	326	323	3
Low Frequency	353	331	22

Single fixation duration. The mean single fixation times for target words preceded by incongruent and congruent previews appear in Table 4. As some participants did not contribute single fixation data for every item, missing participant and item means were substituted with the grand mean for that frequency group, and degrees of freedom were reduced accordingly (i.e., -2df in the participant ANOVA and -4df in the item ANOVA). The main effect of preview, $F_1(1, 42) = 5.63$, $p < .05$, was significant by participants but not by items, $F_2(1, 56) = 1.23$, $p < .50$. Single fixation durations on low frequency words were 22 ms shorter in the syllable-congruent preview condition than in the syllable-incongruent condition. Simple effects tests indicate that the congruency effect was significant in the low frequency words, $F_1(1,42) = 7.64$, $p < .01$; $F_2(1, 27) = 5.49$, $p < .05$, but not in the high frequency words (F's<1). This interaction between preview congruency and frequency was marginally significant in the participant analysis, $F_1(1,42) = 3.21$, $p < .10$, and fully significant by items, $F_2(1, 56) = 7.09$, $p < .01$. The main effect of frequency was significant in the participant analysis, $F_1(1,42) = 15.34$, $p < .001$, and marginal in the item analysis, $F_2(1, 56) = 3.93$, $p < .06$.

Discussion of Experiment 3

Experiment 3 replicated the syllable effect initially reported by Ashby and Rayner (2004). Readers recognized low frequency words more quickly when preceded by a preview that contained the target's exact first syllable, rather than a syllabically incongruent preview that contained one letter more. Together, the present study and Ashby and Rayner's Experiment 2 suggest that skilled readers represent the initial syllable of parafoveal letter strings and use this representation to recognize low frequency words when reading meaningful sentences.

In contrast, fixation durations for high frequency words were comparable in the congruent and incongruent preview conditions, which could suggest that readers did not form prosodic representations of high frequency words. The overall data pattern indicates that the previews affected the recognition of high and low frequency words differently, although the appropriate interactions were significant only by items in both eye movement measures. The absence of preview effects in the high frequency words is consistent with the Jared and Seidenberg (1991) results, and might simply reflect preferred processing of high frequency words along a primarily orthographic route. Were that the case, one would expect robust effects from the three-letter preview condition relative to the two-letter preview, in terms of facilitating reading times for high frequency words. However, no letter effect appeared in this experiment either. Lacking evidence for a letter effect, the reading times on high frequency words cannot be explained easily as reflecting preferential orthographic processing (Jared & Seidenberg, 1991). One possible explanation for the absence of letter effects in high frequency words could be that these words coincidentally had lower frequency initial trigrams than did the low frequency words, and readers, thus, derived less benefit from the three-letter previews of high frequency words. However, a post-hoc analysis using the total frequency counts from

Mayzner and Tresselt (1965) indicated that initial trigram frequencies were comparable for high frequency (15.9 occurrences per 20,000 words) and low frequency words (17.6 occurrences per 20,000 words), $t(62)<1$.

Another possible explanation for the comparable fixation durations in both conditions of high frequency words is that both letter and syllable effects occurred in the high frequency words, but canceled each other out. For the CV-initial words (*secret*), the two-letter congruent previews would have been more phonologically informative, whereas the three-letter previews could have been more orthographically informative. Dual route type theories would account for the additional letter effect in high frequency words based on readers increased reliance on a visual processing route here as compared to the low frequency words. In contrast, Van Orden's verification theory would account for the additional letter effect in high frequency words by a more efficient spell-check process for familiar targets. In any case, how to test whether the comparable means in the high frequency words indicate no preview effect or both letter and syllable effects is not obvious. Although the question of whether frequency affects prosodic processing remains open, the present experiment clearly indicates that skilled readers process the prosodic information in low frequency words during silent reading.

Experiment 4

This experiment examines whether participants use elaborated phonological representations to retain parafoveally-obtained syllable information during a saccade in a modified lexical decision task. As in Experiment 3, an eye-contingent display change technique is used to present participants with parafoveal primes that are syllabically incongruent and congruent with CV target words. In this experiment, however, CV-initial and CVC-initial target words were presented individually on the screen (see Henderson et al., 1995). A modified lexical decision paradigm, referred to here as a *boundary-change lexical decision task*, offered readers advance parafoveal information about a word (Henderson et al., 1995). Participants first fixated a cross on the left side of the computer screen, saw a row of X's, then moved their eyes to the target word on the right and decided whether it is a word. During the time they are programming the saccade to the target (150-250 ms) advance information about the target word is available parafoveally. The boundary-change operates as described in previous experiments; the parafoveal information changes to the target word during the saccade and is not detected by the participant.

The boundary-change lexical decision paradigm differs from a traditional lexical decision task in one critical way. With traditional lexical decision, participants identify words foveally and, therefore, are not required to retain the prime information across a saccade. In contrast, boundary-change lexical decision presents the preview parafoveally and requires participants to preserve the prime information over a saccade in order to facilitate word identification. Finding a syllable congruency effect in the present experiment would imply the involvement of phonological memory processes, perhaps to preserve information across a saccade.

Although this task is no substitute for natural reading, it does minimize a few sources of variability that contribute noise to fixation time data collected during sentence reading. For example, variation in the launch site of saccades to the target affects the visibility of the preview and the foveal processing load on the previous fixation, and these factors affect the extent of parafoveal processing of the preview. In contrast, previews in a boundary-change lexical decision task are presented at a constant visual angle and foveal vision is not occupied by word recognition processes that could interfere with the parafoveal processing of the preview.

One goal of this experiment is to examine whether the syllable congruency effects reported by Ashby and Rayner (2004) were enhanced by differences in initial bigram and trigram frequencies between the two groups of target words (Slattery, personal communication, 2003). If differences in initial string frequency of CV and CVC initial words did contribute to the Ashby and Rayner (2004) effect, then this would suggest that the reported syllable effect is at least partially orthographic in origin. To test this possibility, the materials in the present experiment were chosen such that CV and CVC initial target words were paired by initial trigram (e.g., *secret* and *section*). Also note that both types of target words had initial syllable stress.

Figure 5. Example Materials for Experiment 4

Incongruent Preview	Congruent Preview	Target
sec___	se____	secret
se_____	sec____	section

The predictions for this experiment are similar to those for Experiment 3. If the congruency effect is primarily phonological, then lexical decision times should be faster when words are preceded by a syllable-congruent preview than a syllable-incongruent preview in both the CV and CVC-initial words. This result would confirm the validity of the syllable congruency effect in Ashby and Rayner (2004), and suggest that syllable information is part of the phonological representation that preserves preview information across a saccade. Alternatively, if initial-trigram frequency drove the apparent congruency effect in Ashby and Rayner (2004), then fully counterbalancing the previews in the present experiment should eliminate the syllable congruency effect. This result would suggest that orthographic processing of familiar letter sequences contributed to the preview effects observed in Ashby and Rayner (2004) and Experiment 3.

Methods

Participants. Twenty-six students at the University of Massachusetts were paid or received experimental credit to participate in the experiment. All participants were native English speakers with normal vision who were naive about the purpose of the experiment.

Apparatus and procedure. The apparatus and calibration procedure used was the same as in the previous experiments. At the start of each trial, participants fixated a cross. They were instructed to look at the cross until X's appeared in that location, then look at the word or nonword to the right. The preview appeared parafoveally (2°) at the same time as the X's appeared foveally. The partial word previews supplied two or three of the initial letters of the target and were either congruent or incongruent with its initial syllable. Presentation of the actual target word was triggered by a saccade into the target region, as the eyes crossed an invisible boundary placed one space after the last X (see Figure 6). The participant clicked a response key to indicate whether the foveated letter string was a word or a nonword, and this click ended the trial. The experiment was completed in one session of approximately 30 minutes.

Figure 6. Boundary-Change Lexical Decision Paradigm

A fixation point is denoted by the asterisk(*), and the vertical pipe (|) indicates the invisible boundary.

```
                         *
Fixation 1            xxx|   se____
                              *
Fixation 2            xxx|   secret
```

Materials. Sixty-four target words (see Appendix D) were presented randomly interspersed with 84 unrelated words. The 148 words in the experiment were interspersed with 152 nonword trials. Word and nonword strings were preceded by partial "word" previews. Target words consisted of two groups: CV-initial (e.g., *secret*) and CVC-initial (e.g., *section*) were preceded by partial word previews that contained either the first two or the first three letters of the target, followed by underscores for the remainder of the word. For the CV-initial words (*secret*), the two-letter previews were identical to the initial syllable of the target (*se*____), whereas the three-letter previews were incongruent with the initial syllable, as they contained one more letter than the initial syllable (*sec*___). For the CVC-initial words (*section*), the three-letter previews (*sec*____) were the syllable-congruent condition and the two-letter previews (*se*_____) were the syllable incongruent condition. Underscores followed the pertinent preview information, rather than scrambled consonant strings, in order to eliminate any possible competition effects from those extraneous letters. The CV-initial and CVC-initial words had a mean frequency of 19 occurrences per million words and 9 occurrences per million words, respectively. CV, CVC, and nonwords had a mean length of 5.8, 6.7, and 6.9 letters, respectively. Nonword strings were created by changing one or two of the final letters in real words.

Design. Each participant saw every target word once, with each target preceded by one of its two possible previews. Trials were fully counter-balanced, such that participants saw half of the CV-initial and CVC-initial words preceded by congruent previews and half preceded by incongruent previews. Participants saw each trigram-matched pair of targets preceded either by a preview that was syllabically congruent in both cases (e.g., *secret* preceded by *se____* also read *section* preceded by *sec____)*, or incongruent in both cases (e.g., *secret* preceded by *sec___* also read *section* preceded by *se_____)*.

Results

Lexical decision time was the primary dependent variable, measured as the time between the start of the trial and the button press that ended the trial. As these lexical decision times include the saccade latency, the saccade duration, and the fixation duration, I also report a separate measure of just the total time spent fixating the target before the key press. Preview type (incongruent or congruent) was treated as a within factor in both the participant and item analyses. Word type (CV-initial or CVC-initial) was treated as a within factor in the participant analysis and a between factor in the item analysis. Participant counterbalancing group was included as a between factor in the analyses in order to remove variance due to list in both lexical decision and fixation time

(Pollatsek & Well, 1995). Target word frequency was included as a covariate in the item analyses.

Reaction times over 1500 ms were eliminated from the data set. In addition, trials were excluded from the analyses if the display change occurred before the eyes landed in the target region, if the fixation on the XXX's was under 150 ms, if total fixation time on the target exceeded 1200 ms, or if the word was incorrectly judged to be a nonword. Four items (see items marked * in Appendix D) were excluded from the data set, as they contributed fewer than five data points (from a possible 12 per condition), resulting in the means for 28 CV-initial words and 32 CVC-initial words being analyzed. As a result, four CVC words did not have a corresponding CV partner with the same trigram. As in the previous experiments, the data from participants who met the 75% criterion for usable data were submitted to analyses of variance (ANOVA) by participants (F_1) and items (F_2). This resulted in the loss of 6 data files from a total of 32 participants.

Lexical decision accuracy. The mean accuracy of lexical decisions was 93%. Participants were somewhat more accurate on CV-initial targets (95%) than on CVC-initial targets (92%). Syllable congruency did not affect accuracy rates (F's<1).

Lexical decision latency. Table 5 reports the lexical decision times for CV-initial and CVC-initial words preceded by syllable incongruent and syllable congruent previews. The reaction times reported here are for the complete trial, which includes time spent looking at the X's and the duration of the saccade to the target. Reaction times were 18 ms shorter on average when words were preceded by a syllable-congruent preview than a syllable-incongruent preview. The main effect of preview congruency was significant in the participant and item analyses, $F_1(1, 24) = 6.18$, $p < .05$, $F_2(1, 55) = 6.20$, $p < .05$. Reaction times were 40 ms shorter on average to CV-initial words than CVC-initial words, and the effect of word type was significant in the participant analysis, $F_1(1, 24) = 32.28$, $p < .001$, but not in the item analysis, $F_2(1, 55) = 2.35$, $p < .15$. This difference is probably due to the lower frequency and greater length of the CVC-initial words compared to CV-initial words. The interaction between counterbalancing condition and preview congruency was significant in the item analysis, $F_2(1, 55) = 41.58$, $p < .001$, but not in the participant analysis, $F_1(1, 24) < 1$. The interaction in the item analysis appears due to the overall faster lexical decision times of one counterbalancing group of participants, who contributed shorter mean reaction times to the incongruent and congruent conditions on alternating items. The interaction of word type and preview congruency was not significant (F's<1). A post-hoc division of target words into as high and low frequency groups yielded a significant frequency effect in the item analysis, $F_2(1, 55) = 5.59$, $p < .05$, indicating that participants identified higher frequency words more quickly than low frequency words.

Table 5. Lexical Decision Time (ms) in Experiment 4

	Incongruent Preview	Congruent Preview	Difference
CV-initial Words	979	966	13
CVC-initial Words	1024	1001	23

Eye movement measures. Table 6 reports the mean fixation times for CV-initial and CVC-initial words preceded by syllable incongruent and syllable congruent previews. This measure includes the time spent fixating the target during the trial, from the time that the eyes land on it. Overall, the mean fixation time was 22 ms shorter on average when words were preceded by a syllable-congruent preview than a syllable-incongruent preview. The main effect of preview congruency was significant in the participant and item analyses, $F_1(1, 24) = 13.41, p < .001$, $F_2(1, 55) = 3.84, p < .05$.

Table 6. Total Fixation Time (ms) in Experiment 4

	Incongruent Preview	Congruent Preview	Difference
CV-initial Words	699	675	24
CVC-initial words	730	709	21

CV-initial words were read 33 ms faster on average than CVC-initial words, and the effect of word type was significant in the participant analysis, $F_1(1, 24) = 19.20, p < .001$, but not in the item analysis $F_2(1, 55) = 1.61, p < .25$. The interaction between counterbalancing condition and preview congruency was significant in the item analysis, $F_2(1, 55) = 30.12, p < .001$, but not in the participant analysis, $F_1(1, 24) = 1.03, p < .50$. The interaction of word type and preview congruency was not significant (F's<1).

Mean saccade latencies, or the time spent fixating the X's before the eyes moved to the target, appear in Table 7. When fixating the X's, the two or three letter preview appeared in the participant's parafovea followed by an underscore, as shown in Fixation 1 of Figure 6 above. Readers took a comparable amount of time to program a saccades to CV-initial targets, irrespective of the experimental condition, $t_1(25)<1$; $t_2(31) = -1.25$, p<.25. Saccade latencies to CVC-initial targets differed numerically in the congruent and incongruent conditions, and this difference was significant in the participant analysis, $t_1(25) = 2.08, p < .05$, but did not reach significance in the items analysis, $t_2(31) = 1.36$, *p*<.20. The comparability of saccade latency times in the CV-initial condition indicates that the observed syllable effect for these words did not result from readers getting longer preview in one condition than another.

Table 7. Mean Saccade Latency (ms) in Experiment 4

	Incongruent Preview	Congruent Preview
CV-initial Words	234	236
CVC-initial words	242	228

Additional analyses. A review of the materials in Appendix D indicated that the majority of CV- and CVC-initial pairs differ in the first syllables' vowel sound (e.g., *secret / section*). This pattern raises the possibility of a confound in the data. Perhaps the observed differences in the incongruent and congruent conditions actually stem from differences in the vowel sound activated by the preview, rather than the syllable congruency of the preview. For example, it may be that a preview of *sec* activates the /ɛ/ unit, which is the correct vowel sound in *section* but not in *secret*, and this match is the true source of the facilitation found in the congruent condition.

To test this idea, I selected the five CV- and CVC- initial word pairs that had the most similar vowels in their initial syllables. These pairs were: *solar/solstice*, *vesicle/vespers*, *genocide/gender*, *velocity/velvet*, *delicious/deltoids*. If vowel activation contributed to the effects observed in the larger set of materials, then the effect of preview should be smaller in this subset of vowel-similar pairs. This was not the case, however. Lexical decision times were 33 ms shorter to targets preceded by the syllable congruent preview, compared to the syllable incongruent preview. Mean fixation times were 43 ms shorter in the congruent condition than in the incongruent condition. Pair-wise comparisons of congruent and incongruent means for these ten words were nearly significant for the reaction time data, $t(9) = 2.26$, $p<.052$, and marginal for the eye movement data, $t(9) = 1.84$, $p<.10$. These values are larger than the overall effect size observed in the lexical decision and fixation times (18 ms and 23 ms, respectively), and this suggests that the vowel-similarity between prime and target is not the primary source of the syllable congruency effect.

Discussion of Experiment 4

The boundary-change lexical decision paradigm used here presented parafoveal preview information that could be used to facilitate word identification if participants preserved that information across a saccade. The question was whether participants would preserve the preview information in a simple, linear representation of phonemes or in an elaborated representation that included suprasegmental phonological information (e.g., syllables). The observation of shorter lexical decision and fixation times on words preceded by syllable-congruent previews, as compared to syllable-incongruent previews, suggests that readers represented syllable information available in the parafoveal previews and preserved that information across a saccade. Finding this result with trigram-matched materials indicates that initial letter frequency was not responsible for the syllable effect. Thus, the syllable effect is unlikely to be orthographic in nature.

Experiment 4 provides converging evidence for suprasegmental levels of phonological activation in a lexical decision task that complements the parafoveal effect Ashby and Rayner (2004) initially reported in silent reading of sentences. The General

Discussion of that paper proposed that syllable effects appeared only in the parafoveal preview experiment, because the preview information had to be preserved across a saccade to the target. This is the first lexical decision experiment to demonstrate a syllable effect in English, whereas a previous masked priming lexical decision experiment did not (Ferrand et al., 1997). This could suggest that the intervening saccade between the prime and the target in Experiment 4 permits temporary storage of preview information that may be key to the syllable effect found here. The idea that parafoveal presentation of the preview (or prime) information is necessary for the representation of suprasegmental phonological information is tested more directly in Experiment 5.

Two other aspects of the boundary-change lexical decision paradigm may have contributed to the observed syllable congruency effect. The preview contained no filler characters after the initial two or three letters, and this minimized lateral masking of the most rightward letter in the preview. Second, using multi-syllable nonword foils that were comparable to the targets in length and orthographic structure made these lexical decisions relatively difficult. Thus, participants were encouraged to recognize the target words, rather than accept items as words merely on the basis of orthographic familiarity.

The importance of these aspects of the present paradigm is illustrated by the failure of Ferrand et al. (1997) to find an effect of initial syllable congruency in a masked-priming lexical decision experiment in English. This result led Ferrand et al. (1997) to conclude that syllable units are involved in speech production, but not lexical access– as the naming experiments in that study did find syllable congruency priming effects. However, the short duration of the backward mask (14 ms) may have contributed to the null lexical decision results. This short mask may have allowed readers to hold the prime information in some sort of buffer, without actually storing it in memory. As saccades to the target in the present Experiment 4 masked the preview for a longer duration (approximately 40 ms), readers might have been more likely to store the preview information in short-term memory.

Discussion of Experiments 3 and 4

Two experiments investigated whether readers include syllable information in the pre-lexical phonological representations used in word recognition (Ashby & Rayner, 2004). The central finding is that skilled readers represented the phonological syllable information presented in parafoveal previews and used that information in word recognition on the next fixation. The experiments used different techniques to investigate the nature of pre-lexical phonological representations. In Experiment 3, participants silently read target words in sentences. Syllable information was presented as a parafoveal preview to readers before the target was fixated. In Experiment 4, participants read the target words in isolation and made a lexical decision on each trial. Again, syllable information was presented as a parafoveal preview before the target was fixated. In this experiment, however, CV and CVC-initial target pairs had the same initial trigrams and the previews contained no filler characters. In both experiments, skilled readers processed targets faster in the syllable-congruent preview condition than in the syllable-incongruent preview condition. Obtaining this result with the counterbalanced previews in Experiment 4 affirms that the syllable effect stems from pre-lexical phonological processing. These results suggest that readers begin to activate suprasegmental, as well as segmental, aspects of a phonological representation based on parafoveal information and use that representation in word identification.

The results of Experiment 3 and 4 are inconsistent with the distinct language pathways view discussed in Chapter 1, which holds that skilled reading processes are independent of spoken language processes up until the point of accessing word meaning. If that is true, then the syllable congruency of a preview should not affect word reading times or lexical decision times. Yet both experiments found some effect of syllable congruency. On the other hand, a syllable effect appeared for low, but not high, frequency words in Experiment 3. Therefore, it appears that reading and spoken language processes converge well before lexical access, at least for low frequency words. The absence of a syllable effect in high frequency words is difficult to interpret. This result could be consistent with a distinct pathways model, if the null effect indicates that no suprasegmental phonological effects appeared prior to lexical access. However, it is possible that an effect of syllable congruency was offset by a reverse effect of number of letters in the prime, as the congruent preview for the Experiment 3 targets had one less letter than the incongruent preview. Further research is needed to examine the phonological representation of high frequency words.

In Experiment 4, a syllable effect appeared in lexical decision when the experimental manipulation provided a clear chunk of letters that could facilitate lexical access if it was preserved across a saccade. Readers were not consciously aware of this manipulation, yet they automatically coded the syllable structure as well as the phonemes in the parafoveal previews. This suggests that skilled readers commonly use elaborated representational "frames" in which they store as much phonological information as is available parafoveally, and use it to assist word recognition. The availability of these "frames" could allow stored, parafoveal information to facilitate word recognition and, thereby, decrease the time spent reading a word in foveal view. Thus, it is possible that skilled readers use elaborated phonological representations to speed word identification processes and maintain an efficient reading rate.

CHAPTER 6

THE REPRESENTATION OF SYLLABLE INFORMATION: ELECTRO-PHYSIOLOGICAL EVIDENCE

Introduction

Previous eye movement experiments suggest that readers include syllable information in their parafoveal representations during silent reading of sentences and single words (Chapter 5). As a parafoveal preview of congruent syllable information reduces foveal word processing time, it seems that readers can use syllable information to facilitate word recognition. Yet several questions remain. It appears that readers activate multi-level phonological representations that contain syllable information, but the time course of this phonological process is unclear. Also, the relative consistency of syllable effects in parafoveal preview experiments contrasts with the null effects found for foveal primes in a fast-priming paradigm (Experiment 1 in Ashby & Rayner, 2004). Finding a syllable effect in Experiments 3 and 4, where the advance syllable information was presented parafoveally, suggests that early phonological representations might function to preserve syllable information over the course of the saccade to the parafoveal word. This raises questions about the role of working memory and retinal eccentricity in the syllable preview effect. Is parafoveal preview presentation necessary to observe a syllable effect? Will any task that encourages preview storage, such as a mask between preview and target, utilize the elaborated phonological representations that give rise to a syllable effect?

Experiment 5 addresses these questions by recording event-related potentials (ERPs) during isolated word reading using a four-field masked priming paradigm, which allows quick, foveal presentation of a syllable prime. Readers must retain the prime in memory in order to facilitate word recognition, as the mask following the prime obscures the visual stimulus. Participants silently read single words preceded by a masked prime that contains two or three letters and is congruent or incongruent with the initial syllable of the target word.

Figure 7. Four Field Masked Priming Paradigm

######

PRIME#

######

target

If syllabically congruent primes facilitate word recognition, then the ERP waveforms elicited in the congruent condition should differ significantly from waveforms elicited in the incongruent condition. Given the various time windows in which phonological effects are reported (see the following review of the literature), it is possible that differences between the incongruent and congruent conditions could appear in several time periods. By recording how two and three letter primes impact word identification over time, as well as congruent and incongruent primes, these experiments might reconcile the inconsistent findings of syllable effects and letter effects that have appeared in previous studies (Ferrand et al., 1997; Schiller, 2000).

A handful of recent ERP studies have found phonological effects that peaked earlier than 400 ms post-target. Nisnikiwicz and Squires (1996) examined the relative time course of phonological and semantic processing during word recognition by recording ERPs as participants read pairs of words silently and performed a semantic-relatedness task, and read words in sentence contexts to make sentence acceptability judgments. Target words appeared in four conditions: a correct sentence completion, a homophonous and orthographically similar word, an orthographically similar word, or an unrelated word. Nisnikiwicz and Squires (1996) found an early effect around 200 ms, in the form of a greater negativity to homophone completions, and a semantic effect around 400 ms. In this study, the N400 to semantic incongruity was not modulated in the homophone condition. They interpreted the earlier effect as an N200 component that entailed a mismatch negativity between the given phonological form and its conflicting orthographic forms that primarily indicates the use of phonological information in silent reading. However, Pexman et al. (2002) found longer lexical decision times to homophones, known as a feedback inconsistency effect (Stone et al., 1997), and demonstrated that it arises from competition in the orthographic system that is initially triggered by phonological processes. Thus, the N200 effect seems to indicate the early operation of phonological and orthographic processes, rather than an exclusively phonological effect. Nisnikiwicz and Squires (1996) was the first ERP study to examine single word reading and reading in context to identify pre-lexical activation of phonological representations. As these early phonological effects appeared when reading homophones, it is difficult to determine whether a syllable effect will appear in Experiment 5 at 200 ms post-target.

Bentin, Mouchetant-Rostaing, Giard, Echallier, and Pernier (1999) examined the ERP correlates of orthographic, phonetic, phonological, and semantic processing during single word reading. Participants read over 1300 French words, pseudowords, and nonwords in four variations of an oddball paradigm while their EEGs were recorded. Differences based on orthographic processing were observed at 170 ms post-stimulus, indicated by an increased negativity to letter strings than nonletter strings. Waveform differences at 270 ms post-stimulus indicate that participants distinguished between pronounceable and non-pronounceable targets, irrespective of lexical status. This phonological/phonetic effect involved a greater negativity to pronounceable targets that peaked around 320 ms and had a temporal-parietal distribution. In contrast, maximum semantic effects appeared in waveform differences at 450 ms post-target. The Bentin et al. (1999) data confirm previous findings about the early time course of orthographic processing reported by Nobre, Allison, and McCarthy (1994), and suggest that phonological effects of initial syllable structure should appear 270 - 320 ms.

Barber, Vergara, and Carreiras (2004) used ERPs to examine syllable-frequency effects in Spanish. Participants made lexical decisions to high and low frequency words with high and low frequency initial syllables. Barber et al. (2004) observed an increased positivity to low frequency syllables compared to high frequency syllables at 200 ms post-target, whereas word frequency did not elicit differences in amplitude until 300-400 ms post-target. This syllable frequency effect may not be phonological, however. Rather, it could arise from the frequency of the initial bigram and. thus. be primarily orthographic in nature.

Hutzler. Bergmann. Conrad. Kronbichler. Stenneken. and Jacobs (2004) examined syllable frequency effects in German. using a design similar to Barber et al. (2004). Again. the observed syllable frequency effect appeared as an increased negativity to words with high frequency first syllables between 190 ms and 280 ms. compared to words with low frequency first syllables. The later appearance of lexicality effects suggests a pre-lexical locus for the syllable frequency effect.

Proverbio, Vecchi, and Zani (2004) examined the timecourse of grapheme to phoneme conversion in Italian by presenting participants with single syllable letter sequences that they judged as being contained in the trial target or not. Targets were not presented, instead participants identified the target word by reading a visually presented definition. Proverbio et al. (2004) found increased positivity when the target contained the visual syllable at 215 ms post-stimulus relative to the mismatch condition. Again, the nature of this effect is unclear; it could be essentially phonological or a combination of phonological and orthographic.

Simon, Bernard, Largy, Lalonde, and Rebai (2004) conducted an ERP experiment to examine orthographic and phonological effects on early (pre-N400) ERP components. In Experiment 1, participants simply read words, nonwords, and symbol strings silently during ERP data collection. Their results indicate that readers discriminate orthographic strings from strings comprising non-letter symbols at around 170 ms, whereas the N230 and N320 components were sensitive to phonology as well as lexicality and orthography.

In summary, some previous research indicates that phonological and orthographic effects can appear substantially earlier than semantic effects in the ERP record. Pre-lexical orthographic effects have appeared between 125 ms and 175 ms post-target (Bentin et al., 1999; Nobre et al. 1994; Simon et al., 2004). This is consistent with a MEG study conducted by Kuriki, Takeuchi, and Hirata (1998) that indicated orthographic processing around 150 ms post-target. If an orthographic letter effect appears in the present Experiment 5, it should arise around 150 ms. Pre-lexical phonological effects seemed to arise somewhat later between 200 ms and 320 ms post-target (Barber et al., 2004; Bentin et al., 1999; Hutzler, et al., 2004; Proverbio et al., 2004; Simon et al., 2004), and syllable congruency effects might be expected to appear within that time frame. As no published masked-priming studies have used partial-word primes, it is difficult to predict the time window of effects more precisely.

Pilot Experiment

A pilot experiment with 22 participants explored whether a partial-word masked priming task would elicit any waveform differences during target word reading. The experiment used 72 CV-initial words with second-syllable stress (*demand*) randomly interspersed with 172 unrelated filler items also preceded by masked primes. The procedure and apparatus was identical to that used in Experiment 5 (see Methods, below). A brief masked prime of two letters (DE####) or three letters (DEM###) preceded target words that participants read silently. Between 230 ms and 270 ms post-target word, brain electrical potentials were more negative at four electrode sites (C4, CP3, CPZ, and CP4) in the three letter, syllable incongruent prime condition than in the two letter, syllable congruent prime condition. Between 311 and 330 ms, potentials were again more negative at the same four electrodes in the three letter, incongruent prime condition than in the two letter, congruent prime condition. Although the difference in potentials between conditions was visible at four electrodes, it was not sufficiently widespread and did not persist long enough to be considered reliable. However, the pilot data did suggest that ERPs recorded in a partial-word masked priming paradigm could be sensitive to subtle manipulations in the prime. Based on these pilot data, I conducted Experiment 5.

Experiment 5

Methods

Participants. Twenty students at the University of Massachusetts and Hampshire College were paid or received experimental credit to participate in the experiment. All participants were native English speakers with normal vision who were naive about the purpose of the experiment.

Apparatus and procedure. Electrical potentials were recorded at the scalp via a 32-channel electrode cap with silver/silver-chloride (Ag/AgCl) electrodes arranged in the 10-20 international system (Jasper, 1958) and recorded by a Neuroscan amplifier. A mastoid electrode served as the reference electrode. The electro-encephalogram (EEG) was collected at a sampling rate of 500 Hz while participants read single words preceded by masked primes on a Macintosh black and white monitor set to a display rate of 75 Hz. Superlab software presented the materials and collected manual responses. Event-related potentials were created by epoching around triggers placed at the onset of words of interest, baseline corrected to 200 ms pre-stimulus onset, and artifact rejected over horizontal and vertical eye-electrodes for deflections greater than 70 microvolts. Electrical potentials were re-referenced to the average of right and left mastoid offline. Then the EEG for each electrode was averaged for each participant in each condition, yielding individual averages that were then combined into grand averages for each condition.

Participants were instructed to read each word silently as it appeared on the screen. Trials appeared in black text on a white background, and were viewed through a 3" x 5" window cut into a large piece of white cardboard designed to mask the surrounding visual field. At the start of each trial, a fixation cross appeared at the center of the screen. Target words appeared at the same screen location preceded by partial-word primes that were incongruent or congruent with the initial syllable of the target, followed by a backward mask.

Example Trial	Start (100 ms)	+
	Forward Mask (98 ms)	#####
	Prime (42 ms)	PIL## or PI###
	Backward Mask (98 ms)	#####
	Target Word (644 ms)	pilot

Brain potentials (EEGs) were recorded while participants silently read foveally presented targets and filler items. Semantic judgments, which were requested on half of the filler trials, were made via keypress. The experiment was completed in one 90-minute session.

Materials. Participants read two types of words; CV-initial words (*pilot*) and

CVC-initial words (*magnet*) (see Appendix E). A two or three letter prime preceded each target word. The three-letter prime served as the syllable- incongruent condition for the CV-initial words, whereas the two-letter prime served as the syllable-congruent condition. The inverse was true for the CVC-initial words.

Design. The two sets of target words were randomly presented and intermixed with filler items in a counterbalanced design[2]. Each participant read every target word once, with each target preceded by one of its two possible primes. Materials lists were counterbalanced such that half of the targets were preceded by a congruent prime and half were preceded by an incongruent prime. Each participant read the 98 target words randomly interspersed with 198 unrelated filler items that were also preceded by masked primes. A categorization question ("Is it clothing?") was asked after 99 of the filler items.

Data analysis. Twenty-five electrodes were selected a priori for the analyses. This group excluded the two most frontal sites (FP1 & FP2) as well as the posterior three electrodes (O1, OZ, O2). Missing values for two electrodes (TP7 & T7) were interpolated for three participants by taking the mean value of the three nearest neighbors. All the effects that were reported as significant for the 25 electrodes were also significant at the fifteen electrode sites that required no interpolation (i.e., the middle three columns: F3, FZ, F4, FC3, FCZ, FC4, C3, CZ, C4, CP3, CPZ, CP4, P3, PZ, P4). Waveforms for these 15 electrodes appear in Appendix F.

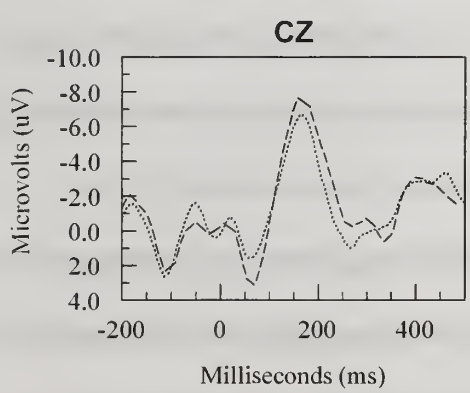
[2] The planned design included fifty words in each of the two groups. A post-hoc review of the script file indicated four coding errors. Two CVC-initial items were miscoded as fillers, and two CV-initial items were miscoded as CVC-initial items.

Inspection of the ERP waveform indicated two time windows for analyses: 125-250 ms and 250-350 ms. The results of analyses are reported for each time window, subsequently referred to as *Early Effects* and *Later Effects*. Waveform differences that occurred earlier than 100 ms post-target were attributed to low-level visual effects and, thus, were not of interest. Initial ANOVA's treated target type (CV-initial or CVC-initial), syllable congruency of prime (CV or CVC), and electrode position (5 levels x 5 levels) as within participant factors in a 2 x 2 x 5 x 5 analysis for each of the two time windows. No main effects of target type (CV-initial or CVC-initial) appeared in either time window; 125-250 ms, $F(1, 19)=1.734$, $p<.25$, and 250-350 ms, $F(1,19)=.080$, $p<1$. Therefore, subsequent ANOVAs included number of letters in the prime (2 or 3) as a factor in the within participants analyses, in addition to syllable congruency and electrode position. Any effect of target type would have appeared as an interaction between number of letters in the prime and syllable congruency.

<u>Results</u>

Early effects (125-250 ms). An increased negativity to the three letter primes (---) appeared in the waveform in this window, $F(1,19)= 9.422$, $p<.01$. Figure 8 presents this main effect for a representative electrode (CZ). A significant interaction

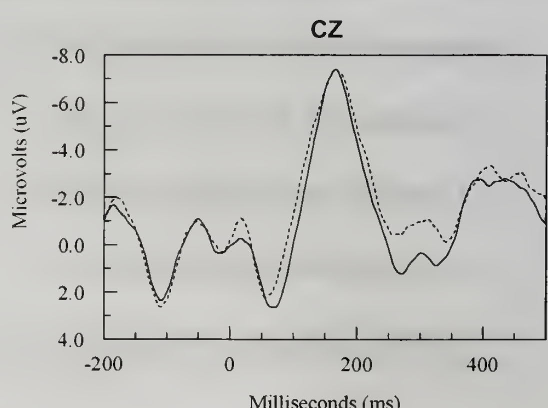
Figure 8.
Effect of Number of Letters in Prime (125-250ms)



between letters and rows, $F(4,76) = 3.232$, $p<.01$), indicated that the effect was concentrated over fronto-central sites. No interaction appeared between letter and columns, $F(4,76) = 1.427$, $p<.25$, which suggested that the effect was distributed bilaterally. Syllable congruency effects were absent in this early window, $F<1$. As the primes here were fully not counterbalanced for the CV and CVC initial words, it is unclear whether the main effect in this early time window is due to the number of letters in the prime, or to low-level visual differences in the primes.

The last 25 ms of this time window and the first 25 ms of the next window were also analyzed separately to determine the offset of the letter effect and the onset of the syllable congruency effect. Significance was tested conservatively, avoiding any interpolation, at the midline-15 electrode sites (2 number of letters x 2 syllable congruency x 3 columns x 5 rows). Letter effects were significant between 225 ms and 250 ms, $F(1,19) = 8.663$, $p<.01$, but no longer significant between 250 ms and 275 ms, $F(1,19) = 3.711$, $p<.10$. Syllable congruency effects were not significant between 225 ms and 250 ms, $F(1,19) = 1.625$, $p<.25$, but did reach significance between 250 ms and 275 ms, $F(1,19) = 4.864$, $p<.05$.

Figure 9.
Effect of Syllable Congruency (250-350ms)



Later effects (250-350 ms). An increased positivity appeared in the waveform that was elicited by the syllable-congruency (——) between the prime and the target word, and this main effect of syllable congruency was significant, $F(1,19)= 7.629$, $p<.01$. Figure 9 presents the main effect of syllable congruency between prime and target for a representative electrode (CZ). The congruency effect did not interact with any other factors, all Fs<1. The prime effect observed in the earlier window was absent in this later window, $F<1$.

Discussion

Experiment 5 investigated whether suprasegmental, syllable information presented in brief masked primes modulated the ERPs elicited during target word reading. Between 125 ms and 250 ms, ERPs were more negative to targets preceded by three letter primes than two letter primes. This effect could be orthographic or a result of low-level visual differences in the primes. Between 250 ms and 350 ms, ERPs were more positive to targets preceded by syllable-congruent primes than syllable incongruent primes. This later phonological effect (Bentin et al., 1999; Simon et al., 2004) suggests that readers represented suprasegmental phonological information during word recognition, and extends the parafoveal syllable effects observed in Ashby and Rayner (2004) to foveally presented words. As speakers and listeners activate suprasegmental information during language processing also, the syllable congruency effect supports the claim that skilled readers initiate access to spoken language representations en route to lexical access and, thus, offers converging evidence that is inconsistent with the distinct pathways model.

Experiment 5 may help reconcile the inconsistent results of syllable effects or letter effects in previous eye movement experiments (Ashby & Rayner, 2004). The appearance of possible early letter effects and later phonological effects in the ERP record during silent reading constitutes preliminary evidence that readers process various grain sizes of information prelexically, from single letter or phoneme units to multi-segment units. Therefore, it seems likely that different experimental paradigms (e.g., parafoveal preview vs. fast-priming) detect different aspects of this pre-lexical information. More sensitive paradigms are more likely to detect several aspects of pre-lexical representations. The present experiment investigated whether the method of prime presentation constrains the appearance of syllable effect. Syllable congruency between the prime and the target elicited an increased positivity around 300 ms, relative to the incongruent condition, in this masked priming paradigm. This result suggests that neither a parafoveal presentation of the prime, nor an intervening saccade is necessary to obtain a syllable effect. However, the failure to find a syllable effect in fast-priming (cf., Ashby & Rayner, 2004, Experiment 1) suggests that some interruption of the visual stimulus between the prime and target is required for a syllable congruency effect to arise (e.g., a backward mask). The implications of this finding for identifying the locus of the syllable congruency effects are addressed in the General Discussion.

According to similar logic, the present ERP results might shed light on the inconsistent findings in previous research on the role of syllables in speech production (c.f., Brand et al., 2003; Ferrand et al., 1997; Schiller, 2000). Because syllable effects occurred later in word recognition, they might be more vulnerable to experimental task constraints. For example, naming task participants might use the number of letters in the prime to facilitate the programming of the onset of articulation without activating full phonological representations. If readers can short-circuit the typical route used in word recognition when under time pressure, then studies with unusually short naming latency means (Schiller, 2000) should only find letter effects, whereas studies with more typical naming latency means might tend to detect syllable effects (Ferrand et al., 1997).

In summary, the results of this experiment provide converging evidence that readers use elaborated (rather than minimal) phonological representations, indicate the necessity of interrupting the prime stimulus for syllable priming to occur, and may account for inconsistent findings of letter and syllable effects in the previous production research. Additionally, Experiment 5 could potentially make a methodological contribution to the word recognition literature. If future ERP experiments replicate the syllable effect found here, then the partial-word masked priming paradigm may prove to be a sensitive tool for investigating the detailed nature of the phonological representations used in reading.

CHAPTER 7

GENERAL DISCUSSION

The five experiments presented here investigated the nature of early phonological representations in skilled silent reading. Do the early phonological representations used in skilled reading resemble the multi-layered representations used in processing spoken language? Establishing "resemblance" involved examining whether readers used both segmental and suprasegmental phonological information to facilitate word recognition. The main theoretical question was whether readers use minimal phonological representations for lexical access, as suggested by the distinct pathways model, or activate elaborated phonological representations early in word recognition. Minimal phonological representations might not fully represent some segments, such as vowels, or might consist only of phonological segments and omit suprasegmental information, such as syllable structure. The data from these five experiments consistently suggested that skilled readers used elaborated phonological representations during silent reading and began activating these representations parafoveally, or prior to lexical access.

Experiments 1 and 2 monitored eye movements during sentence reading to determine whether the representations used in word recognition include vowel segments as well as consonants. Parafoveally presented vowel information from nonword previews facilitated word recognition when the preview vowel was similar to the target vowel, as compared to when the preview vowel differed from the target vowel. This facilitation appeared irrespective of the orthographic relationship between preview and target, indicating that skilled readers typically represent phonological vowel segments.

Experiments 3, 4, and 5 examined whether skilled readers included syllable information in the phonological representations formed prior to lexical access. Experiment 3 monitored eye movements during sentence reading, such that high and low frequency target words were preceded by previews that constituted the target's first syllable or one letter more then the first syllable. Reading times for the low frequency targets were faster in the syllable congruent preview condition than in the syllable incongruent condition. This result replicates the syllable congruency effect found in the second experiment in Ashby and Rayner (2004). Experiment 4 monitored eye movements during a boundary-change lexical decision task to test whether a syllable congruency effect would appear in lexical decision when syllable information appeared parafoveally. Decision times and fixation times were faster for targets preceded by syllable congruent previews than previews with one more or one less letter. In Experiment 5, ERP's were recorded as readers silently read words preceded by syllable congruent and incongruent primes in a masked priming paradigm. Waveform differences indicative of word processing appeared 250 - 350 ms post-target, such that the syllable congruent condition elicited a greater positivity than the incongruent condition. Experiments 3, 4, and 5 offer converging evidence that skilled readers typically activate elaborated phonological representations that include syllable information en route to word recognition.

In combination, the results of Experiments 1- 5 suggest that skilled readers activated elaborated phonological representations, which included segmental and suprasegmental information, prior to lexical access. Thus, these data are not consistent with the distinct pathways view of word recognition, which claims that skilled readers primarily use a visual route to word recognition and do not typically activate speech-like phonological representations until lexical access. As refuting the distinct pathways view hinges on the evidence that readers initiate elaborated phonological representations pre-lexically, a summary of that evidence might be useful at this point. In Experiments 1 and 2, the parafoveal presentation of the phonological vowel in the context of a nonword indicates the pre-lexical nature of the representation of vowel segment information. Experiments 3 and 4 used parafoveal previews that consisted of word fragments, and lexical access was not possible at the time the syllable information was presented. Likewise, the masked foveal primes in Experiment 5 were word fragments that did not permit lexical access. In each case, readers activated segmental and suprasegmental information before either could be accessed from a lexical entry. Thus, the present data contradict the minimality principle, which proposes that only a partial phonological code is used in lexical access (Berent & Perfetti, 1995; Frost, 1998).

The novel contribution of the present experiments is the elaborated nature of these pre-lexical phonological representations. In order for readers to use the advance phonological information to identify words during the next fixation, they had to preserve it across the intervening saccade. If readers use only minimal phonological representations during word recognition, as proposed by Frost (1998), then such a representation would not preserve suprasegmental syllable information across a saccade. However, if readers activate whatever advance phonological information is available, and hold that information in elaborated speech-like representations across the intervening saccade to the target, then this could account for the observed syllable congruency effect.

Thus, the vowel and syllable effects observed here indicate that skilled readers begin activating multi-level phonological representations before they fixate and identify the target word.

Skilled readers' elaborated phonological representations are speech-like in the sense that they can include suprasegmental information. This information appears to be represented when it is available from print, as the syllable information was in Experiments 3-5, and when it must be retrieved from memory (e.g., the representation of lexical stress information reported in Ashby & Clifton, 2005). Obviously, it is possible that early reading representations differ from spoken language representations in some way, but future experiments are needed to demonstrate that. For the purpose of this discussion, the similar nature of these reading representations and spoken language representations is taken as an indication that skilled readers begin activating spoken language representations in the early phases of word recognition.

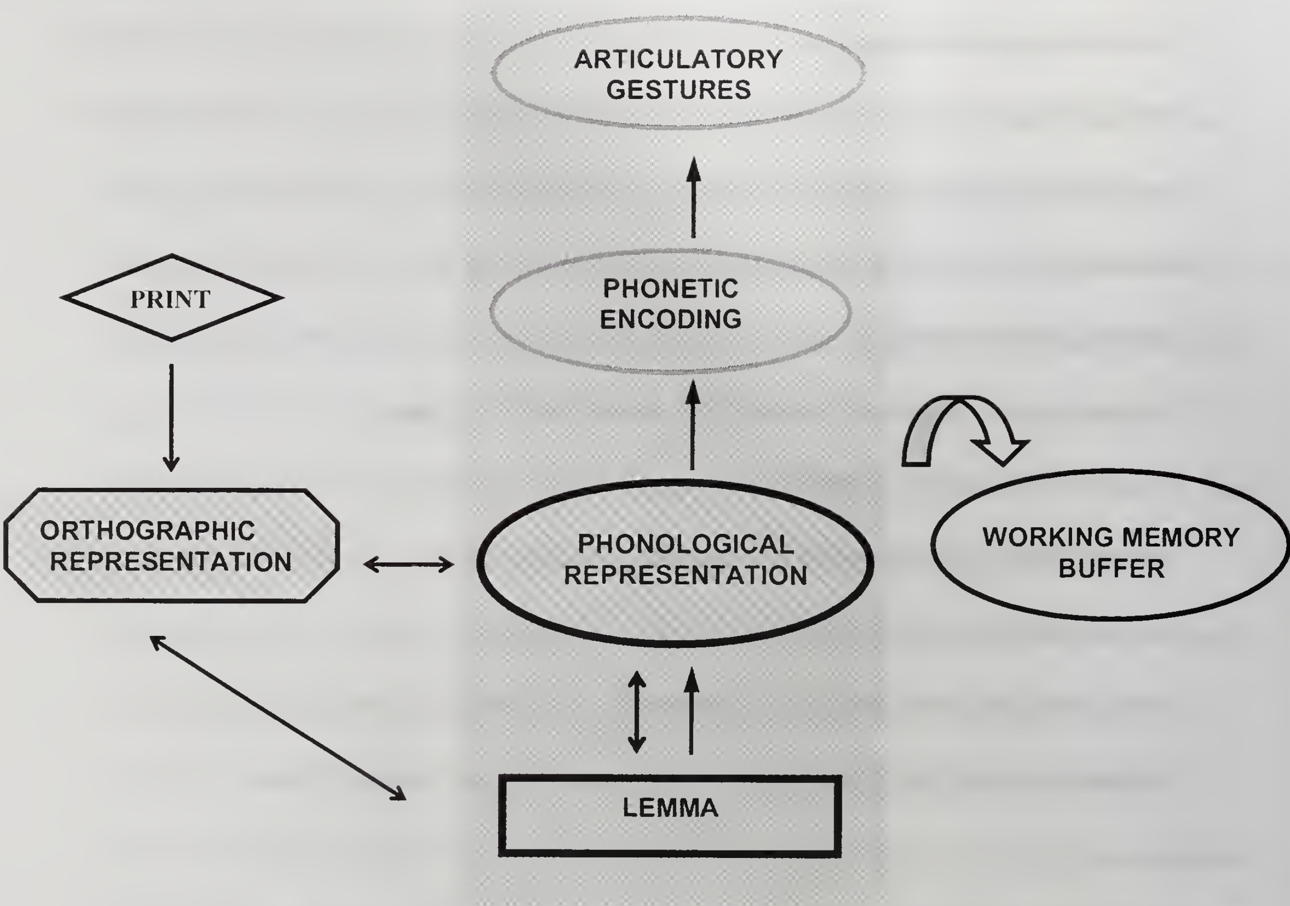
This raises the question of why skilled readers bother to activate and maintain prosodic phonological representations when reading silently. Figure 10 illustrates what I will call the *phonological hub theory* of word recognition. Here, I claim that word recognition processes interface with the language production system through a phonological hub that consists of a prosodic phonological representation.

Figure 10. Phonological Hub Theory

The Phonological Hub Theory of word recognition during silent reading describes the interface between word reading and language production. The language production portion (the shaded rectangle) is adapted from Levelt et al.`s (1999) theory.

☐ Processed parafoveally.

☐ Processed parafoveally and preserved across the saccade to the target.



Phonological hub theory situates word recognition processes in the context of adults' everyday reading experiences in order to describe how readers recognize words when silently reading meaningful sentences. It accounts for parafoveal processing of an upcoming word, foveal processing when that word is fixated, and the output of word recognition to the memory buffer that feeds sentence processing. As such, it entails an assembly of word recognition, production, and memory processes that interface through a central hub of phonological representation. The phonological hub illustrates the centrality of phonological representation for skilled reading; it enables readers to maintain parafoveal information to facilitate word recognition when the word is fixated, and to maintain the word in working memory once it has been recognized.

The shaded rectangular area in the middle of Figure 10 is the production core of phonological hub theory adapted from the language production model proposed in Levelt et al. (1999). Levelt et al. (1999) claim that phonological representations in production become syllabified in an on-line process that occurs somewhere in the transition from phonological to phonetic representations (Cholin, Schiller, & Levelt, 2004). In contrast, Dell's (1986, 1988) production theory claims that syllable information is included when a phonological representation is activated. As these data are consistent with either assumption, Levelt's model is utilized here mainly due to the convenience afforded by its transparency. In this adaptation of Levelt et al. (1999), word production processes proceed from the bottom to the top of the figure in the feed-forward fashion, as described by the solid-capped one-way arrows (⟶). Phonological hub theory claims that skilled reading processes exploit production modules interactively (⟷) to activate prosodic phonological representations that can be held in memory for later sentence processing.

According to this theory, the following series of events occur in the process of skilled word recognition during silent reading. A printed word is initially processed parafoveally by encoding the letter string into orthographic units. From this point, processing occurs along two routes (cf., Harm & Seidenberg, 2004). The orthographic representation activates semantic information and activates the word's phonological representation that includes phonemic segments and syllable units. Assuming that the saccade to the target functionally masks the orthographic information, as modeled by Harm and Seidenberg (2004) in Simulation 14, it is the more durable phonological representation that preserves the parafoveal information across the saccade. On fixation, the phonological representation refreshes the orthographic representation and activates semantic information. Inputs from the orthographic and phonological representations converge on a pattern of semantic activation that identifies a specific lemma. At this point, parafoveal processing of the next word begins (Pollatsek, Reichle, & Rayner, 2006). For the currently fixated word, lexical identification processes access memory stores that supply the missing prosodic information to "fill in" the elaborated phonological representation if needed. Once the full phonological representation is complete and uploaded into working memory, the eyes saccade to the next word. Thus, phonological hub theory describes how skilled readers form prosodic phonological representations during silent reading.

Phonological hub theory also makes claims about why readers form elaborated phonological representations. Logically, it seems that phonological representation at some point during silent reading is necessary in order to connect written language processes to core spoken language processes that maintain verbal information in memory (Frost, 1998; Burgess & Hitch, 1999). The early interface of reading systems with spoken language processes observed in the present experiments may benefit reading efficiency and reading comprehension processes in several ways. Reading efficiency benefits because readers can begin forming prosodic representations in advance of an actual fixation, and use that parafoveal information for lexical access on the next fixation. Including syllable information in a parafoveal representation, thus, entails a head-start on activating an elaborated prosodic representation. Such phonological representations could support comprehension during silent reading, as readers maintain phonological representations in a verbal memory buffer that can later be accessed by sentence integration processes (Newman & Connolly, 2004; Perfetti, 1999; Taft & Van Graan, 1998). If having a word form available for storage in memory is a goal of word recognition, then completing an elaborated prosodic representation of a word might play a role in eye movement control, as suggested in Ashby & Clifton (2005). In that case, the sooner skilled readers complete activation of a fully elaborated phonological representation, the sooner their eyes move to the next word.

By extension, activating elaborated phonological representations during silent reading might contribute to developing fast and accurate word recognition skills. Keeping the eyes fixated until a full phonological representation forms could allow time for an orthographic verification process to complete in tandem with the phonological representation, as in the Harm and Seidenberg (2004) computational model. Thus, forming elaborated phonological representations could facilitate the phonological and orthographic co-activation that contributes to the formation of high quality lexical representations in skilled readers (Perfetti & Hart, 2002).

To summarize, the present experiments suggest that skilled readers begin activating elaborated, prosodic representations of a word before actually fixating it. As these representations include suprasegmental information (Experiments 3-5) as well as segmental information (Experiments 1 and 2), they seem similar in nature to the phonological representations used in spoken language. Phonological hub theory proposes that reading processes interface with language production processes early in word recognition through an elaborated, prosodic phonological representation common to both systems. This raises the intriguing possibility that language production is involved in visual word recognition.

APPENDIX A

MATERIALS FOR EXPERIMENT 1

Previews

Discordant	Concordant	Sentences
braum	*braim*	Molly enjoyed her short *break* in the afternoon.
braim	*braum*	The crane lifted a *broad* beam onto the ship.
blorm	*blerm*	Becky would often *blurt* out the wrong answer in class.
chorg	*cherg*	Beth listened to the birds *chirp* in the back yard.
clewm	*cleem*	Robert's house always looked *clean* after the maid came.
craid	*craud*	Kathy watched the baby *crawl* across the floor.
daik	*dauk*	Jim waited until *dawn* to begin fishing the river.
draim	*draum*	The model was quickly *drawn* by the art students.
doist	*dowst*	The argument left little *doubt* in the minds of the jurors.
faib	*faub*	Ellen watched the young *fawn* eat the meadow grasses.
fewns	*feens*	Margaret cooked a huge *feast* for Thanksgiving last year.
flaru	*flurn*	Liza would sometimes *flirt* with the guys she met at the bar.
floim	*floam*	The exotic pets were *flown* in from South America.
ghoab	*ghoob*	Andrew dressed like a *ghoul* for the Halloween party.
graub	*graib*	Susan's MP3 player had *great* sound and it was lightweight.
groab	*groob*	Corey helped start a support *group* for victims of crime.
lail	*laul*	The buyers replaced the large *lawn* with a rock garden.

lewm	*leem*	The grocery only sold *lean* cuts of meat.
laib	*loob*	Some photographers take *lewd* pictures of women.
paim	*paum*	Abbey took the last *pawn* in the chess game.
poid	*powd*	Most of the time, Elizabeth would *pout* if she lost the game.
proit	*prowt*	Sam's brother looked *proud* when he received the award.
shaib	*shaub*	Deborah knitted her first *shawl* this year.
sharg	*sherg*	Carmen kept every *shirt* that belonged to her father.
soab	*soob*	For the party, Alice made *soup* and a salad.
staub	*staib*	Benjamin tasted every *steak* on the table.
stewn	*steen*	The pictures showed *steam* rising from the hot springs.
storp	*stirp*	The sailor mopped the wide *stern* of the ship.
straim	*straum*	The waitress put *straws* in all of the sodas.
tharn	*thern*	Jason hoped to take *third* place at the track meet.
tharnt	*thernt*	The young lion's *thirst* called him to the river bank.
troid	*trowd*	Sally ordered the baked *trout* for dinner.
voit	*vait*	Emma chose a black *veil* for the funeral.
yaim	*yaum*	Carl would often *yawn* during his morning class.

APPENDIX B

MATERIALS FOR EXPERIMENT 2

Previews

Discordant	Concordant	Sentences
blook	*bloon*	Cathy hoped the flowers would *bloom* before... vacation.
blort	*blomp*	Amy saw the reddish *blobs* of clay drying in the sun.
bort	*bomp*	Most mothers have a close *bond* with their children.
chead	*chean*	Anne went to the store to buy *cheap* wine for the party.
chead	*chean*	Derek thought that he should *cheat* on the Spanish exam.
clall	*claff*	Betty found the best *class* available at that time.
clall	*claff*	Sue knew that the shoes would *clash* with her dress.
drook	*droon*	Beverly said that all babies *drool* when they are teething.
drook	*droon*	Jessica's feathers might *droop* in the heat from the lights.
fook	*foon*	Claire tried to *fool* her teacher with a fake doctor's note.
gort	*gomp*	The tribe pleased their *gods* by sacrificing small animals.
jort	*jomp*	Dawn quit one of her several *jobs* during finals week.
jort	*jomp*	Every day, David *jogs* with his wife in the park downtown.
nort	*knomp*	The couple chose wooden *knobs* for their kitchen cabinets.
nort	*nomp*	The candidate's speech got several *nods* of approval.
pead	*pean*	Anna climbed to the highest *peak* of the mountain.
prook	*proon*	The lawyer wanted to find *proof* of his client's innocence.
rall	*raff*	Paul set the doughnuts on a long *rack* until they cooled.

rall	*raff*	The baby's latest *rash* kept her from sleeping.
schook	*schoon*	Unlike Charlene, Tom hated *school* when he was a child.
scook	*scoon*	Joe ordered a large *scoop* of chocolate ice cream in a dish.
slall	*slaff*	Bob let the rope hang *slack* while he tied up the boat.
slort	*slomp*	The twins looked like *slobs* in their ragged sweat pants.
snall	*snaff*	Jessie ate her sweet *snack* early today.
spead	*spean*	Although Donald is nervous, he should *speak* clearly.
squead	*squean*	Sally wanted the loud *squeak* in the hardwood floor fixed.
squead	*squean*	William would always *squeal* when his sister tickled him.
stook	*stoon*	Aaron moved his *stool* closer to the fireplace.
stread	*strean*	Karl walked beside the cold *stream* for several miles.
stread	*strean*	Lenore wiped the purple *streak* of lipstick off the mirror.
thall	*thaff*	Amy hoped that she could *thank* her brother in person.
trall	*traff*	Andy ran around the paved *track* until he was out of breath.

APPENDIX C

MATERIALS FOR EXPERIMENT 3

High Frequency

The trainer helped the young colt *become* a champion racehorse.

The station broadcasted the latest *development* in the Middle East conflict.

After dating a few months, Alice and Jonathan *began* to fight often.

Every day, Tammy walked *behind* her brother all the way to school.

Terry hoped to find a good *position* in an advertising firm.

Liza reported the latest *society* news in her weekly column.

The younger children still *believed* in Santa Claus, and they got teased for it.

Margaret chose a pretty *material* for the dress that she planned to make.

Alexandra was very *religious* until she went away to college.

Claire wondered if she would *remember* to get groceries on her way home.

Sam didn't know what *direction* he was headed until he saw the familiar sign.

Tom knew that he could *design* a better logo if he had more time.

The insurance adjuster couldn't *determine* how much damage was done by the fire.

Janice studied harder and hoped for a better *result* than last time.

Andrew's parents didn't *require* him to do any chores during the summer.

Ellen's father helped her make good *financial* decisions after she graduated.

As soon as she got her license, Molly could *begin* driving her new car.

The dryers had a larger *capacity* than Anne needed.

John made a firm *decision* to quit smoking next week.

The captain of the ship *remained* on the top deck.

The students did not discuss local *political* issues at the meeting.

Tammy asked if she could *return* the shirts without a receipt.

Bob got through the tight *security* at the airport, but his luggage did not.

The children were told not to swim *beyond* the markers of the diving area.

John worried that the scandal would *diminish* the value of his stock.

The recording said that the plane *departed* at the scheduled time.

Bob invested his money so that he could *retire* by the time he turned fifty.

Beth bought her father a large *cigar* for his birthday.

The spies were trained to quickly *detect* any suspicious activity.

Isabelle was the chief editor, and she could *reject* any story she wanted.

The newly-organized band *negotiated* a new contract.

<u>Low Frequency</u>

The students urged the bank to *divest* from South Africa.

The brilliant lawyer could *refute* the eyewitness testimony.

Alex would only *deceive* his parents as long as it was necessary.

Elizabeth didn't feel *remorse* for her father's death until years later.

Sally planned to *replace* the brown linoleum in the bathroom.

Robert was surprised by his sister's *timidity* during the hiking trip.

Ed wanted to explore the large *botanical* garden before they left the city.

The manager of the small *casino* watched the blackjack dealers closely.

Alice knew that her old cat would *devour* the mouse that it caught.

Anna listened to her daughter *recite* the poem in Spanish.

George found out that he could *default* on his student loans.

Elsie made a major *donation* to the homeless shelter last year.

The author discovered that the third *reviewer* did not like the paper.

Eric loved to watch classic movies about *rebellious* teenagers and runaways.

The priest hoped that Albert would *repent* for his sins.

Meredith made chocolate pudding with *bananas* in it for the party.

Sally thought that melons were simply *delicious* to eat for breakfast.

Mark planned to avoid the play *rehearsal* next week.

Megan thought that her scars were *repulsive* so she kept them hidden.

Astronomers can find *miraculous* events in the night sky.

Larry noticed that Bill *monopolized* every conversation.

Susan and Ed wanted *genetic* testing before they decided to have children.

Robert planned to sell his farm to a big *developer* next year.

The corn was genetically modified to stay *resistant* to local pests.

The professor wrote the first *definitive* textbook about city planning.

A counselor could *facilitate* an agreement between the man and his wife.

Jim left his name with the cute *receptionist* in the front office.

George waited for the slow *pedestrian* to cross the street.

Kim asked the store clerk about *reversible* jackets.

After getting a raise, Sarah *repaid* the loan she got from her parents.

Fred tried to look *polite* and interested, but he found the conversation boring.

Josh feared that the coffee growers would *revolt* if prices dropped any lower.

Helen grew to *resemble* her grandmother.

APPENDIX D

MATERIALS FOR EXPERIMENT 4

CV-initial Target Words	CVC-initial Target Words
bonus	bondage
bacon	bacteria
cosign	costume
halo	halter
facial	faction
solar	solstice
disyllabic*	dismal
soma*	somber
music	muslin
semen	semblance
visa	vista
pilot	pilgrim
bison	biscuit
vinyl	vintage
vesicle	vespers
vacancy	vaccinate
genocide	gender
salient	salvage
silent	silver
pastry	pastor
pretext	pretzel
comatose*	comfort
mason	mascot
fragrant*	fragment
magic	magnet
pony	ponder
tidal	tidbit
helium	helmet
basin	basket
juniper	junkie
velocity	velvet
delicious	deltoids

*items with < 5 data points were excluded from the statistical analyses

Nonword Foils

disselt
cocktalt
debane
pastroy
tampes
procrastinole
deposilt
tempent
nudise
regact
manifent
phosphon
secume
rabims
banapa
decap
radialt
vintape
debrast
primage
divineng
wandem
diminist
vibratint
ravipe
reflen
profoult
siblint
plastiv
perplege
dangepe
reductone
challepe
situatine
Promotone
Detectine
Suspelt
Marginath
Suppone
Lethargin
Boisterose
Capacify
Quotatine
Yesterday
Impressite
Centump
Conflint
Deliberate
Postume
Ruminefe
Possibilafy
Rambunctive
Benint
Bizarme
Cantens
Careis
Collapte
Continem
Defuncd
Devoil
Diffusa
Digent
Diluke
Dissemt
Donale
Durens
Fermont
Forbud
Gazelte
Humave
lamporn
burgunly
persint
rampaque
rotunct
seclute
sextint
sublive
suffict
similatice
surmice
tormenat
refrest
petide
manuve
denope
cohene
captious
betrag
negligant
retiremant
latemt
semblonce
bacterim
tormelt
yondes
cobrat
punishmens
sensuat
migroft
selent
tactife
mastoden
topican

APPENDIX E

MATERIALS FOR EXPERIMENT 5

CV-initial Targets		CVC-initial Targets	
bovine	covert	bondage	membrane
cadence	motive	cadmium	mildew
cipher	savage	censor	mundane
cushion	reflex	cinder	muslim
devious	salient	cistern*	nectar
divers	savior	comrade	nostril
facial	sequel	cosmos	pelvis
famine	tigress	culprit	pompous
favors	vacate	deltoid	rafter
feline	vagrant	dismal	rupture
futile	vibrant	faction	rustic
jovial	votive	fender	segment
kosher	demon	festive	semblance
latent	minus	fumble	sensual
migrant	modify	gambit	tactile
nitrate	basin	gender	tamper
pastry	pagan	halter	tempest
nudist	poker	jasper	tidbit
possum	recipe	jumble	velvet
rabies	rover*	lactate	vintage
radiant	super*	badminton	viscous
cider	decency	lender	vulture
fragrant	vacancy	camper	wander
viper	botany	falter	yonder
spider	tulip	magnet*	zombie

*miscoded items

APPENDIX F

SYLLABLE CONGRUENCY EFFECT (250-350 ms)

Subject:
EEG file: 2congrusy2.avg Recorded : 16:50:56 16-Sep-2003
Rate - 500 Hz, HPF - 0.15 Hz, LPF - 30 Hz, Notch - off

Neurosoft, Inc.
SCAN 1.2
Printed : 12:16:03 03-Oct-2005

---------- Syllable Congruent Prime

_______ Syllable Incongruent Prime

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